Contents lists available at ScienceDirect

# Renewable and Sustainable Energy Reviews

# The role of non-thermal plasma technique in NO$_x$ treatment: A review

P. Talebizadeh [a], M. Babaie [b], R. Brown [b], H. Rahimzadeh [a,*], Z. Ristovski [b], M. Arai [c]

[a] Department of Mechanical Engineering, Amirkabir University of Technology, Tehran, Iran
[b] Biofuel Engine Research Facility, Queensland University of Technology, Brisbane, Queensland, Australia
[c] Department of Mechanical System Engineering, Gunma University, 1-5-1 Tenjin-cho, Kiryu, Gunma, Japan

A B S T R A C T

Non-thermal plasma (NTP) has been introduced over the past several years as a promising method for nitrogen oxide (NO$_x$) removal. The intent, when using NTP, is to selectively transfer input electrical energy to the electrons, and to not expend this in heating the entire gas stream, which generates free radicals through collisions, and promotes the desired chemical changes in the exhaust gases. The generated active species react with the pollutant molecules and decompose them. This paper reviews and summarizes relevant literature regarding various aspects of the application of NTP technology on NO$_x$ removal from exhaust gases. A comprehensive description of available scientific literature on NO$_x$ removal using NTP technology is presented, including various types of NTP, e.g. dielectric barrier discharge, corona discharge and electron beam. Furthermore, the combination of NTP with catalyst and adsorbent for better NO$_x$ removal efficiency is presented in detail. The removal of NO$_x$ from both simulated gases and real diesel engines is also considered in this review paper. As NTP is a new technique and is not yet commercialized, there is a need for more studies to be performed in this field.

© 2014 Elsevier Ltd. All rights reserved.

## Contents

* Corresponding author. Tel.:+98 21 66405844; fax: +98 21 66419736.
  E-mail address: rahimzad@aut.ac.ir (H. Rahimzadeh).

# 1. Introduction

There has been a continuous increase in the number of diesel engines operating in both stationary and mobile applications, due to their lower operating cost, higher thermal efficiency, longer durability, and their lower hydrocarbon (HC) and carbon monoxide (CO) emissions [1]. However, these engines emit higher amount of $NO_x$ and particulate matters (PM) than gasoline engines. Moreover, conventional energy sources are close to extinction, and environmental concerns necessitate cleaner fuels being used. Indeed, exhaust emission regulations have become much more stringent in recent times. Alongside these increasingly stringent emission standards, there is still considerable concern that unregulated pollutants are having a deleterious effect on human health and the environment generally [2–7]. Given the likely health effects associated with gaseous pollutants and ultra-fine particles, there is a clear need to monitor the emissions of diesel engines.

## 1.1. Diesel engine emissions

Diesel engines are used as the power source in a wide variety of industries and their applications are growing rapidly all over the world. Diesel engines have been employed in transportation as the power source for buses, trucks, trains and ships. Moreover, they are used in power plants for power generation, and also in farming, construction and industrial settings. In spite of the large number of diesel engine applications, they continue to produce significant amounts of pollution, particularly $NO_x$. Therefore, their increasing numbers in transportation vehicles will cause an increase in global emissions, with nitrogen oxides being the main pollutant from diesel exhaust.

Inside an engine, the complete combustion of the fuels composed exclusively of carbon and hydrogen, will only generate $CO_2$ and $H_2O$, to the exclusion of any other harmful products. However, a very short time is enough for the chemical oxidation processes in combustion chambers; the lack of homogeneity in the mixture, and the heterogeneity and rapid variations in the temperature do not allow for the ideal state of thermodynamic equilibrium to be reached [8]. Thus, the incomplete combustion of hydrocarbons results in the formation of a wide range of organic and inorganic compounds distributed among the gaseous, semi-volatile and particulate phases [9] as is schematized in Table 1 [10].

Diesel exhaust differs from gasoline engine exhaust in two major ways. Firstly, diesel exhaust contains a far higher amount of $NO_x$. Secondly, the exhaust is far leaner, that is, it contains far less unburned hydrocarbon and carbon monoxide than a typical exhaust from gasoline engines. Thus, nowadays, the focus of the research on reduction of harmful emissions is mainly focused on $NO_x$ [11].

## 1.2. Health and environmental impacts of $NO_x$ and emission legislation

Several types of nitrogen oxides exist in the environment: $N_2O$, NO, $NO_2$, $N_2O_3$, $N_2O_4$, $NO_3$, and $N_2O_5$. The abbreviation $NO_x$ usually relates to nitric oxide, nitrogen monoxide (NO) and nitrogen dioxide $NO_2$, which can be called 'fresh' nitrogen oxides from a photochemical point of view, since they reach atmosphere in these forms. Another important nitrogen oxide is nitrous oxide ($N_2O$), and it may also be called 'fresh' for the same reasons [12]. Nitrogen oxides form when fuel is burned at high temperatures, as in a combustion process. The primary sources of $NO_x$ are motor vehicles (49%), electric utilities (27%), industrial, commercial, and residential sources (19%) and all other sources (5%) that burn fuels [13].

Among the various types of $NO_x$, nitric oxide and nitrogen dioxide are considered toxic. Around 95% of $NO_x$ emitted from incineration processes is NO and 5% $NO_2$ [14]. Nitric oxide is less toxic than nitrogen dioxide. However, as with most radicals, NO is unstable and reacts readily with oxygen through photochemical oxidation to form $NO_2$ [12].

Studies focused on risk assessment have showed that high outdoor $NO_2$ concentrations observed in residential areas contribute to increased respiratory and cardiovascular diseases and mortality [15]. Some of the other negative effects of $NO_x$ are acid rain, ground-level ozone (smog), photochemical smog, global warming, nose and eye irritation, visibility impairment, the formation of toxic products and water quality deterioration [16].

$NO_x$ is responsible for tropospheric ozone/particulate (urban smog) through photochemical reactions with hydrocarbon [17]. The mixture of $NO_x$ and volatile organic compounds (VOC) in the atmosphere when exposed to sunlight can result in the formation of photochemical smog which can cause the infection and encourage the spread of cancer. The yellowish color of $NO_2$ decreases the visibility, contributes to heart and lung problems and can suppress plant growth. $NO_2$ can also react with radicals produced from VOCs in a series of reactions to form toxic products such as peroxyacetyl nitrates (PAN) [17–19].

NO and $NO_2$ together with sulfur dioxide ($SO_2$) are the major contributors to acid rains [17]. When $NO_x$ and $SO_2$ are exposed to the atmosphere, they react with water to form sulfuric acid and nitric acid, which are the main components of acid deposition.

**Table 1**
Typical diesel exhaust composition [21].

|  | Component | Concentration |
| --- | --- | --- |
| Components naturally occurring in air | $N_2$ | 70–75 vol% |
|  | $O_2$ | 5–15 vol% |
|  | $CO_2$ | 2–12 vol% |
|  | $H_2O$ | 2–10 vol% |
| Regulated harmful components | CO | 100–10000 ppm |
|  | HC | 50–500 ppm, C1 |
|  | $NO_x$ | 30–600 ppm |
|  | $SO_x$ | Proportional to fuel S content |
|  | PM | 20–200 mg/m³ |
| Unregulated harmful components | Ammonia | 2.0 mg/mile |
|  | Cyanides | 1.0 mg/mile |
|  | Benzene | 6.0 mg/mile |
|  | Toluene | 2.0 mg/mile |
|  | PAH | 0.3 mg/mile |
|  | Aldehydes | 0.0 mg/mile |

**Table 2**
$NO_x$ emission standards for diesel vehicles [36,37].

| Year | Reference | Light duty diesel (g/km) | Heavy duty diesel (g/km) |
|------|-----------|--------------------------|--------------------------|
| 2000 | Euro I    | –    | 0.36  |
| 2005 | Euro II   | –    | 0.15  |
| 2008 | Euro III  | 0.5  | 0.10  |
| 2010 | Euro IV   | 0.25 | 0.02  |
| 2011 | Euro V    | 0.18 | 0.005 |

Indeed, $NO_2$ reacts with OH in the atmosphere to form nitric acid ($HNO_3$). Nitric acid can also form when nitrogen dioxide ($NO_2$) reacts with the nitrate radical ($NO_3$) in the presence of atmospheric water or aldehydes. Nitrogen oxides account for approximately 30% of all acid deposition [20]. Nitrous oxide ($N_2O$) has some negative effects as well. $N_2O$ is a greenhouse gas that has a global warming potential more than 300 times higher than that of carbon dioxide [21]. $N_2O$ can destroy the stratosphere ozone which increases UV-B radiation at the earth's surface [22]. Furthermore, animal and human studies indicate that the toxic effects of $N_2O$ depend on concentration and time. For a time-weighted average of 100 ppm for an eight-hour workday and/or a time weighted average of 400 ppm per anesthetic administration, it would provide adequate protection of dental personnel and be acceptable with existing pollution control methods [23]. However, in patients who have been administered $N_2O$ for extended periods of time, and the neurological abnormalities found in health care workers who inhaled $N_2O$ recreationally, some effects like anesthetic action and bone marrow depression [23] have been disproved.

The health effects of breathing in diesel exhaust have been shown to be toxic, mutagenic or carcinogenic in animal exposure tests [24]. Also, the exposure of animals to diesel exhaust has produced morphological and biochemical changes in the lungs, with an increase in susceptibility to bacterial infection, and the possibility of producing systemic toxic effects. Some human diseases that can be caused from $NO_x$ are pulmonary edema (swelling), bronchitis, and even pneumonia [25]. Due to the negative effects of $NO_x$ on health, regulation of exhaust emissions has recently become increasingly stringent. Government legislation for permissible exhaust emission standards was first introduced for light-duty vehicles only, in both Europe and the United States in 1982, and then for heavy-duty engines in 1990 [26]. In Table 2, emission regulations concerning $NO_x$ are indicated as shown, with more and more stringent standards being employed day by day [27,28].

Furthermore, Euro VI regulations will come into force in 2013, which will enable the harmonization of the European standards with those of the US and Japan [29,30].

### 1.3. $NO_x$ removal after treatment systems

Up until now, several technologies have been applied for $NO_x$ removal from exhaust gases. Selective catalyst reduction (SCR), active lean $NO_x$ catalysts, lean $NO_x$ trap catalysts and multiple injection combustion have been considered for $NO_x$ removal in automobile and stationary engines [31–33]. SCR is used to convert $NO_x$ into diatomic nitrogen ($N_2$), and water ($H_2O$), with the aid of a catalyst i.e. a gaseous reductant such as anhydrous ammonia, aqueous ammonia or urea [34,35]. Zeolite catalysts will be also the mainstay for Japan, US, and Euro VI applications [30]. The advantage of using SCR is that the major byproducts of SCR are harmless nitrogen and water vapors. However, SCR catalysts need high temperatures (around 300 °C) for activation. There are some problems in using SCR catalysts, such as the possibility of ammonia leakage, catalyst poisoning, catalyst discharge under high temperature conditions or through the influence of sulfur, and the need for the construction of urea solution stations [12,36]. In addition, diesel exhaust is a highly oxidizing environment, and the SCR catalysts used on gasoline engines are not suitable for $NO_x$ removal in diesel applications [37].

Active lean $NO_x$ or $DeNO_x$ catalysts are another important $NO_x$ reduction, after-treatment system, while the reductant is different from the SCR catalysts. They employed hydrocarbons as the $NO_x$ reductant [38] and in the reduction process, $NO_x$ reacts with hydrocarbons and produces $N_2$, $CO_2$, $H_2O$ and $N_2O$. Both $CO_2$ and $N_2O$ are greenhouse gases with great global warming ability [39,40]. Moreover, in the active system applications, it is necessary to add supplementary HC to the exhaust gas occasionally to maintain the reactions.

Lean-burn $NO_x$ trap (LNT) catalysts include three main components. The first is noble metal such as Pt, which enables NO oxidation in the lean-burn phase and $NO_x$ reduction in the rich-burn phase. The second component contains a storing element such as Ba, which captures $NO_x$ as nitrates or nitrites. The third component has a large surface area to increase noble metals and storage medium, which consists of the supports such as $Al_2O_3$ [41]. Some of the disadvantages of the system are high cost of the catalyst and noble metal as well as a regeneration requirement periodically [42].

Multiple injection and high pressure fuel injection is applied in order to reduce both soot and $NO_x$ emissions from combustion simultaneously [43]; however, it is not an after treatment system. The technique can optimize emission from the combustion chamber and has advantages such as reduction of pollutants and noise, higher thermal efficiency and power and lower specific fuel consumption [44]. Although this technique can reduce toxic combustion by-products from the exhaust gas, an after-treatment system is still required to meet the current increasing emission standards.

The NTP technique can be considered for emission reduction in diesel engines fueled by diesel or biodiesel. NTP treatment of exhaust gas is a promising technology for $NO_x$ removal, which is effective through the introduction of plasma inside the exhaust gases. Plasma is the fourth state of matter, consisting of positive and negative charges, which have a tendency to remain electrically neutral overall, and over large length scales. It is composed of free electrons, ions, radicals, atoms, and molecules in various states of excitation [45]. Vehicle exhaust gases, both diesel and gasoline, undergo chemical changes when exposed to plasma. Logically, oxidation processes dominate in the presence of oxygen. These reactions include oxidation of hydrocarbons, carbon monoxide, and nitrogen oxides [46].

This review paper provides an overview of the literature concerning $NO_x$ removal from exhaust gases, as conducted by various groups of researchers. The first part of this review is about diesel engine emissions. The second section contains an overview of power supply technologies and their applications on plasma treatment of exhaust gases. The final section provides a summary of findings as to how plasma can be effective for $NO_x$ removal from simulated gases and diesel engines, whilst highlighting the significance of exploring various views concerning plasma emission treatment as held by a number of researchers. The main argument presented in this section suggests that there is a strong correlation between mechanical, chemical and electrical parameters involved in plasma production and exhaust gas treatment, which will ultimately result in the improvement of diesel engine emission treatment. This review paper seeks to bring together in a systematic way the disparate material on $NO_x$ removal from exhaust gases.

## 2. Plasma and various power generators

The term plasma was first introduced by Irving Langmuir (1881–1975) and his colleague Lewi Tonks (1897–1971) in 1929, to describe the inner region of a glowing ionized gas phase produced by means of an electric discharge in a tube [47]. Plasma is the fourth state of matter, that is, an ionized gas into which sufficient energy is provided to free electrons from atoms or molecules and to allow species, ions and electrons to coexist. Generally, plasma is electrically neutral. The plasma ionization degree is the proportion of atoms that have lost (or gained) electrons [45].

As discussed before, in order to introduce plasma into a gas, the electronic structure of the species (atoms, molecules) should be changed and then excited species and ions will be produced. The required energy for this process can be provided by thermal force, or carried by either an electric current or electromagnetic radiations [48]. Therefore, plasma is divided into thermal or hot plasma and non-thermal or cold plasma. In the thermal variety, molecules dissociate into the atoms at high temperatures around 2000 °C. Gas molecules will be ionized by losing electrons if the temperature goes up to more than 3000 °C. In this state, gas has a liquid-like viscosity at atmospheric pressure and the free electric charges confer relatively high electrical conductivities that can approach those of metals [49]. In thermal plasma, the kinetic energy (temperature) of charged particles and the kinetic energy (temperature) of the background gas are similar. Since all particles are in thermal equilibrium, thermal plasma is also known as equilibrium plasma [50]. In non-thermal plasma (NTP), the electric field transmits energy to the gas electrons and then energy will be transferred to the neutral species by collisions [48]. In NTP, electrons have a kinetic energy higher than the energy corresponding to the random motion of the background gas molecules, generally in the range of between 10,000 K and 100,000 K (2–3 order of magnitude greater than the background gas) [51]. An example of non-thermal plasma is the gas filling a fluorescent tube. Its temperature is only around 40 °C, but the temperature of free electrons in the system exceeds 10,000 °C [46]. The intent when using non-thermal plasma is to selectively transfer the input electrical energy to the electrons, which then generate free radicals through collisions, and promote the desired chemical changes in the exhaust gas. These reactions can be accomplished with just a fraction of the energy that is required in the thermal plasma system [51–53].

Generally, three kinds of power generators (namely AC, DC and Pulse) can be used in order to generate plasma. AC and Pulse energisations show a superior $NO_x$ removal efficiency, when compared with DC energisation. However, Pulse energisation is found to be more energy efficient [54].

Pulsed power is generated instantaneously but gradually delivering the energy accumulated and stored in an energy component to a load. By releasing stored energy over a very short time interval, a huge amount of peak power can be delivered [55]. In other words, the energy, which can be generated with extra low voltage, is released in a shorter period of time, which causes higher amplitude [56]. This strategy is called pulsed power. Many studies of industrial applications of pulsed power technology, such as food processing, medical treatment, water treatment, ozone generation, engine ignition, ion implantation, exhaust gas treatment and others, have resulted from the development of pulsed power generators [56,57].

Recently, repetitively operated pulsed power generators with a moderate peak power have been developed. These generators are compact, reliable, low maintenance, and have high reproducibility. Using pulsed power technology, non-thermal plasmas have been generated by a pulsed electron beam [58] or a pulsed streamer discharge [59], and can be used to treat nitric oxides ($NO_x$), sulfur dioxide ($SO_2$), carbon dioxide ($CO_2$), particulate matter and volatile organic compounds (VOCs), and also to generate ozone. Non-thermal plasmas have many kinds of chemically activated radicals, such as O (Oxygen radical), $O_3$ (Ozone), N (Nitrogen radical), N* (excited Nitrogen radical), $N_2^+$ (positive ions of nitrogen) and OH, which are generated by the dissociation and ionization of the ambient gases caused by the impact of energetic electrons [57,60,61].

When plasma is introduced inside the exhaust gases, oxidation processes will be started. $NO_x$, unburned hydrocarbons, carbon monoxide (CO) and particulate matter (PM) will be oxidized [62]. In spite of $NO_x$ reduction to $N_2$ and $O_2$, plasma treatment of exhaust gases is more related to NO oxidation to $NO_2$ [63,64]. The plasma is believed to show potential to improve catalyst selectivity and removal efficiency.

## 3. Plasma reactors

NTP can be generated in several ways, such as through electrical corona discharges, radio frequency discharges, microwave discharges [65,66], dielectric barrier discharges and electron beams. The following NTP technologies are considered for pollution reduction in engine exhaust gases, with each having its advantages for different applications. The plasma reactors can be divided into different categories with respect to the type of power supply (DC, pulse, DC and pulse, AC, AC and DC, RF), the presence of a dielectric barrier or catalyst, geometry, mode of discharge, polarity, and voltage level and gas composition. Therefore, the comparison of NTP reactors is complicated due to the dependency on different aforementioned conditions [67,68] and there are no well-established common criterion for comparing different plasma reactors. Based on this finding, we propose the criterion such as energy density, removal efficiency, energy efficiency, residence time, pressure drop, scalability and cost for future plasma reactor research.

### 3.1. Electron beam

An electron beam is formed in a separate generator, such as a cathode tube, and then the electrons will be injected into the exhaust gas. The energy of the electrons is absorbed by the components of the gaseous mixture proportionally to their mass fraction [69]. The energy of electrons can be much higher in the e-beam reactor than in other reactors. Disadvantages of the e-beam reactor include the need for a special reactor for generating the electrons, and poor efficiency in transferring the electrons into the exhaust gas [46,70,71].

### 3.2. Corona discharges

The term corona comes from the crown-like appearance of the plasma discharge when the voltage exceeds a certain value [72]. In a corona discharge reactor, a non-uniform electric field is formed between two concentric electrodes by the sharp edges or points of its electrodes where the radius of the curvature is small. In other words, the mode of discharge in corona discharge is usually the streamer mode and the ionization zone is spread over the entire gap. Therefore, the discharge gap can be set as large as 10 cm or more, which is highly appropriate for large scale application [67]. A characteristic of corona discharges is that there is no need to use a dielectric to generate plasma [73,74]. In corona discharge, the strong electric field, ionization and luminosity are actually located close to one of the electrodes and the electric current is transferred to the outside electrode by the drift of charged particles in the relatively low electric field [75]. Therefore, a low current and, as a result, very low discharge power, is

achieved and increasing the applied voltage can form a spark. This problem can be solved by using pulse voltage circuits. The produced pulsed electric field can prevent plasma from going into the thermal mode and forming an arc [46,75].

In some environmental applications such as decomposition of $CCl_4$ [71], pulsed corona processing is found to be considerably less energy efficient than the electron beam processing. However, the requirement of using a separate reactor and difficulty of electron generation is an important limiting factor for application of electron beam processing.

### 3.3. Dielectric barrier discharge

The basic design of a dielectric barrier discharge (DBD) reactor consists of a set of electrodes with at least one dielectric barrier between them. As a result of the presence of the dielectric barrier, the discharges require higher voltage for their operation. In other words, the electric field must be high enough to cause breakdown in the gas [76]. The gas is passed through the dielectric surfaces, while the electrodes produce the sufficient electrical field between them to form the plasma. The material used for dielectric barriers is usually quartz glass, silica glass or alumina; however, they can also be made from ceramic materials, and thin enamel or polymer layers in special cases [46,76].

A common feature of both DBD and corona discharge is that small scale electron streamers are formed [73]. However, a DBD produces a homogenous discharge with low energy consumption and this discharge process is also the mechanism through which charges are transported [77]. Furthermore, DBD can avoid spark formation inside the streamer channels, which are therefore called silent discharges, and the absence of sparks causes the absence of overheating, local shock waves and noises [75]. High discharge power can also be achieved without employing pulse power generators [75]. Whealton et al. [73] explained that after applying the electric field perpendicular to the dielectric, electron streamers are formed. Space charge then builds up on the dielectric surface, locally terminating the external applied electric field, and then finally extinguishing the discharge. Eventually, in a DBD reactor the large volume excitation of the glow discharge with the high pressure of the corona discharge can be formed [78]. Therefore, in general, employing the dielectric has two benefits: firstly, limiting the charge transferred by an individual micro-discharge and so preventing the formation of arc discharge, and secondly, spreading the micro-discharge over the electrode surface, which increases the probability of collision between the electron and ions and gas molecules [79].

In addition to the easy formation of stable plasmas and homogeneous discharge in DBD, there are some more advantages such as scalability, effectiveness and low operational cost which cause researchers to use DBD more than other types of reactors [76,80]. Furthermore, the discharge characteristics depend on the gas composition, type of dielectric material, and operating conditions of voltage and frequency [67]. According to the above advantages of DBD, it has more potential for exhaust cleaning from CO, $NO_x$ and VOCs [64] and DBD reactors have been used for a long time for ozone generation [81].

### 3.4. Dielectric packed bed reactor

The dielectric packed bed reactor is similar to the DBD, but with a different configuration of dielectrics. Pellets of dielectric material are placed in the gap between the barrier and the electrode. One advantage of this system is that relatively low applied voltages can be used to form a plasma over a relatively large separation of the electrodes [74]. In other words, when the pellets are exposed to an external electric field, a spontaneous polarization occurs in the direction of the electric field, resulting in a high electric field at the contact points of the pellets [67]. Another advantage of this system is that it is possible to use catalyst pellets, which make this type of reactor a possible choice for plasma–catalyst systems. In the plasma–catalyst systems, the plasma discharge is introduced right on the catalyst surface, which enhances the properties of the catalyst and its corresponding performance [82]. Furthermore, residence time is proposed as one of the common criteria to compare different plasma reactors [83]. Residence time can be improved by using pellets in dielectric packed bed reactors. However, the high pressure drop and attrition of the pellets are disadvantages of this system [46].

### 3.5. Surface plasma discharge

In this system, one of the electrodes covers one side of the dielectric barrier completely; however, the other electrode only partially covers it, making it distinct from the surface discharges and DBD. The plasma is generated next to this dielectric surface, which is in contact with the gas. When the electric field is applied, the surface plasma covers the entire dielectric surface [73]. A feature of this discharge is that after a few nanoseconds, charge begins to build up at the dielectric surface, which has the effect of reducing the electric fields outside the dielectric, eventually extinguishing the discharge [46].

### 3.6. NTP reactor comparison

Energy consumption in an NTP application for emission reduction is a major challenge. Specific energy density (SED), which is defined as the ratio of discharge power to the gas flow rate, and energy efficiency, which is the ratio of the substance removal measure to the plasma energy, are the common criteria in NTP energy evaluation. Some studies about the effect of NTP processing in conversion of NO to $N_2$ and $O_2$ show that the specific energy consumption of corona discharge, DBD and dielectric packed bed reactors are all similar [84,85]. In the decomposition of bromomethane, ($CH_3Br$), and tetrafluoromethane ($CF_4$), it was shown that DBD and dielectric packed bed reactors have better energy performance, thus showing higher performance than corona discharge reactors [83].

On the other hand, the energy efficiency of NO removal from the air was found to be higher for surface plasma than the corona and DBD reactors as reported by Malik et al. [86]. However, they outlined the dependency of NO removal to gas composition especially to oxygen concentration. Besides that, the energy efficiency of DBD and corona discharge reactors was found to be reduced with an increasing of the discharged energy, while for surface plasma it remained constant. This indicates a greater potential for using surface plasma reactors at high energy densities and in more compact reactors than conventional DBD or corona reactors [86].

Therefore, for the proper applications of NTP reactors it is necessary to consider not only the physical properties (such as voltage, frequency, ionization, geometry, type of power supply, volume, etc.) but also the variations in energy efficiency. It is still controversial to compare NTP reactors with the same physical properties, regardless of the mode of the application and gas composition [67,71,83–85]. It has also been shown that the design of a reactor and the materials of the electrodes can greatly affect removal and energy efficiency [87].

## 4. Plasma $NO_x$ removal

After introducing different plasma reactors in the previous section, we now analyze different publications concerning the application of

NTP on $NO_x$ removal. Firstly, the relevant chemical reactions have been presented. Then, the relevant publications for the engine exhaust and simulated exhaust have been reviewed in two main categories. In each category, a variety of publications for different types of reactor have been considered.
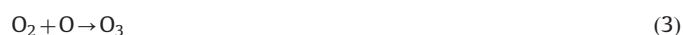
$NO_x$ storage reduction (NSR), selective $NO_x$ recirculation (SNR) and non-thermal plasma have been considered increasingly in recent times, with a view to developing techniques to reduce $NO_x$ emissions in diesel engines [63,88–90]. Non-thermal plasma (NTP) technology has been introduced as a promising method for $NO_x$ removal from simulated gases as well as real diesel engine exhaust. In an NTP reactor, $NO_x$ concentration is reduced by a set of reactions between free electrons, ions, radicals, atoms, and molecules which are formed in plasma. The $NO_x$ reduction reactions generally can be divided in two groups:

$NO_x$ removal reactions

and

NO–$NO_2$ conversion reactions.

In the first group, some of the primary and main $NO_x$ removal reactions could be summarized as the following [63,91–95]:

$$N_2+e \rightarrow N+N+e \tag{1}$$

$$NO+N \rightarrow N_2+O \tag{2}$$

$$O_2+O \rightarrow O_3 \tag{3}$$

$$N_2+e \rightarrow e+N_2(A) \tag{4}$$

$$N_2(A)+NO \rightarrow N_2+N+O \tag{5}$$

$$N_2(A)+N_2O \rightarrow 2N_2+O \tag{6}$$

$$NO_2+N \rightarrow N_2+O_2 \tag{7}$$

where $N_2(A)$ represents $N_2$ metastable state.

The second group of reactions (which involves the reactions of oxidizing NO to $NO_2$) could be summarized as the following [63,94–96]:

$$O_2+e \rightarrow O+O+e \tag{8}$$

$$NO+O \rightarrow NO_2 \tag{9}$$

$$O_2+O \rightarrow O_3 \tag{10}$$

$$NO+O_3 \rightarrow NO_2+O_2 \tag{11}$$

Hydrocarbons are attributed an important role in $NO_x$ removal by using plasma discharge. The reaction paths for $NO_x$ removal change significantly from that without hydrocarbon additives. In the presence of hydrocarbons, the efficiency of $NO_x$ reduction and NO–$NO_2$ conversion is greatly increased due to the reactions between the hydrocarbons and $NO_x$ such as [46]

$$C_3H_6+OH \rightarrow C_3H_6OH \tag{12}$$

$$C_3H_6OH+O_2 \rightarrow C_3H_6OHOO \tag{13}$$

$$C_3H_6OHOO+NO \rightarrow C_3H_6OHO+NO_2 \tag{14}$$

Furthermore, the NO–$NO_2$ conversion due to the oxidation by O/OH radicals or by hydrocarbons is less probable since the O/OH radicals decrease in the presence of soot inside the diesel engine exhaust. Moreover, some $NO_2$ can react with soot by the following reaction [97]:

$$NO_2+soot \rightarrow CO+CO_2+N_2+H_2O+NO \tag{15}$$
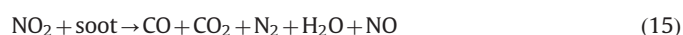
In addition, in the presence of water, some other reactions are also involved, which are as follows [98]:

$$H_2O+e \rightarrow OH+H+e \tag{16}$$

$$NO+OH \rightarrow HNO_2 \tag{17}$$

$$NO_2+OH \rightarrow HNO_3 \tag{18}$$

and

$$NO+H_2O \rightarrow NO_2+OH \tag{19}$$

Therefore, the reactions taking place during the treatment of actual diesel exhaust vary largely from that of the simulated gas mixtures, due to the presence of various hydrocarbons, aldehydes and water in the diesel exhaust.

On the other hand, many studies suggest that the conversion of NO to $NO_2$ is an important intermediate step in the reduction of NO to $N_2$ [99], and that the most efficient way to do this is to use a plasma reactor along with an additional catalyst reactor. In the first step, the plasma oxidizes NO to $NO_2$ in the presence of HC [100]:

$$Plasma+NO+HC+O_2 \rightarrow NO_2+HC-products \tag{20}$$

In the second stage, the catalyst reduces $NO_2$ to $N_2$ by selective reduction using hydrocarbons [100]:

$$Catalyst+NO_2+HC \rightarrow N_2+CO_2+H_2O \tag{21}$$

In general, some researchers have employed NTP using different combinations of gases to simulate real exhaust gases from engines, in order to examine the ways that different parameters affected the system [98,101–117], while others have studied real engines to enhance the efficiency of the NTP [37,54,96,97,100,110,118–132].

Various kinds of NTP reactors were studied by the researchers. The earlier kind of NTP reactors were electron beam reactors, which were mostly employed from 1980 to 2000 [133–136]. The majority of researchers applied dielectric barrier discharge (DBD) reactors [37,96,97,101,115–117,120–127,130–132]. Some used packed bed DBD reactors [37,54,102,105,120,124,127,137] and others used DBD assisted reactors along with another catalyst or adsorbent reactor [96,102,106,108,121,122,125–127,130,131]. However, some researchers studied corona reactors [100,103,104,107,109,110,118,119,128,129]. In addition, some researchers examined surface plasma discharge reactors [86,98,113]. Note that in some studies, the packed bed DBD reactor is called a single stage plasma-catalytic system, with the catalyst or adsorber placed in the discharge zone. The DBD assisted reactor (used with another catalyst or adsorbent reactor) is also called a two-stage system, with the catalyst or adsorbent placed downstream of the plasma. The advantage of single-stage reactors is that the active species reacts on the catalyst surface in the discharge zone. However, in the two-stage systems, the oxidation of NO to $NO_2$ in the plasma increases the catalyst performance, since the $NO_2$ removal is better than the NO removal near the catalyst [138].

### 4.1. $NO_x$ removal from simulated gases

#### 4.1.1. Corona reactor

In 2000 and 2001, Namihira et al. [103,104] studied the effects of pulse-width in improving $NO_x$ removal efficiency. They designed a new DC voltage generator in the order of 10 ns pulse-width. A corona discharge reactor and gas cylinders of $N_2$, NO and $H_2O$ were used, and the concentration of NO and $NO_2$ was measured at ambient temperature. They studied low pulse frequencies ranging from 1 to 13 pps (pulses per second) and various pulse widths from 40 to 120 ns. It was shown that the removal ratio of NO decreased with an increasing pulse repetition rate and an increasing pulse-width. However, the removal energy efficiency increased with a decreasing pulse-width. In other words, the

removal energy efficiency was higher for shorter pulse-widths at a fixed NO removal ratio. The authors claim that their results are clearly in coincidence with another study which used electron beam irradiation without any additive [139,140]. The removal energy efficiency for the comparison was calculated as follows:

$$NO_E = \frac{(G/22.4\,[l/\min]) \times (NO_i - NO_e) \times 60\,[\min/h] \times 10^{-3}}{f \times E}[mol/kWh]$$

(23)

where $f$ is the pulse repetition rate [pulses/s], $E$ is the input energy to the reactor per pulse [J/pulse] and $G$ is the gas flow rate [lit/min].

In 2004, $NO_x$ removal mechanism by a DC corona discharge has been considered by Arai et al. [107]. A mixture of $N_2$, $O_2$, and NO was used as the test gas. In their experiments, oxygen concentration was changed between 0 and 20%. The initial concentration of NO was kept at 100 ppm and the residence time inside the reactor was 17 s. It was shown that the $NO_x$ removal mechanism depends on oxygen content. In the case of $NO+N_2$ mixture, the NO reduction process has been controlled by exited $N_2$ radicals. However, in the case of $NO/N_2/O_2$ mixture, NO mainly was converted to $NO_2$ and $N_2O_5$ by ozone generated from corona discharge.

In 2006, Saito et al. [109] studied the effect of $H_2O$, $CO_2$, $CH_4$ and $C_2H_4$ on NO removal by using a DC corona discharge. The base gas in their experiments was a mixture of $N_2/O_2$ (20%)/NO (100 ppm) and the coexisting gases were added to the base gas. They considered both positive and negative discharge in their tests. When moisture was added to the base gas, $NO_x$ removal was 30% at energy density of 50 J/L in the case of positive corona discharge and 90% at 250 J/L for negative discharge. It was found that the existence of $CO_2$ in the base gas was not desirable. When $CO_2$ was added to the base gas, the $NO_x$ concentration increased up to twice at 920 J/L compared to the case of $CO_2$ free for positive discharge. In the case of negative discharge, about 200 J/L more energy was needed to get 90% $NO_x$ reduction compared to the base case. In the case of $C_2H_4$ addition, NO was oxidized to $NO_2$ for positive discharge and $NO_x$ was hardly removed. However, $NO_x$ was decreased with a lower energy density in the case of negative discharge. In the case of simulated gas ($N_2/O_2/NO/H_2O/CO_2/C_2H_4$ mixture), the $NO_x$ removal efficiency was more than 90% and the energy density was lower compared with the base gas. However, some byproducts such as CO, $O_3$, $NO_3$, and $NO_2$ have been increased in the case of simulated gas.

### 4.1.2. DBD reactor

Mizuno et al. [101] in 1998 investigated NTP at very low temperatures of below 100 °C. Different simulated gases ($NO+O_2$, $N_2O$, $O_2$, $N_2$, $CO_2$ and $H_2O$ gas cylinders) were examined to simulate the exhaust of a thermal power plant. A straight wire DBD reactor was used for all simulations. The concentration of NO and $NO_2$ was measured at three different temperatures: room temperature, liquid nitrogen temperature and solid ethanol temperature. The voltage source for this study was pulse DC voltage, and the maximum supplied voltage and pulse frequency was 30 kV and 60 Hz respectively. At low temperature, it was claimed that the plasma process is effective to remove gaseous pollutants, as well as to promote plasma chemical reactions. To cite one particular case, the removal efficiency of nitrogen (DeNO) at room temperature was 20%, at liquid nitrogen temperature ($-196$ °C) it was 60% and at solid ethanol temperature ($-114$ °C) it was 98%. Note that the removal efficiency or removal ratio was defined as follows:

$$NO_R = \frac{(NO_i - NO_e) \times 100}{NO_i}$$

(22)

The influence of gas flow rate on the removal efficiency of NO was also studied, and showed that the DeNO decreased when increasing the gas flow rate from 1 to 8 L/min, because the gas exposure to the electrical field decreases. It was also shown that by decreasing the temperature, the discharge power decreased at a fixed input power. In this paper, although it was reported that the plasma-treated gas was more effective at low temperature, no clear reasons were outlined. A real engine was not studied, and an extremely low temperature was considered, which is not applicable in everyday situations.

Wang et al. [114] conducted a complete investigation on the effects of electrode connection, diameter, material, shape of the inner electrode, and dielectric material on NO removal in order to improve the performance of dielectric barrier discharge reactors. The simulated gas examined in this paper is the combination of NO and $N_2$. An AC power supply with a peak voltage of 30 kV and peak frequency of 10 kHz was employed. The specific energy density (SED) parameter is considered to compare different case studies. For the same removal efficiency, it is better to have a lower specific energy density, regarding energy consumption. If the SED parameter of 10 J/L (for a 3-L-class diesel engine) can be achieved, which is around 3% of automotive diesel engine power output over the United State Federal Test Procedure (US FTP) test cycle, it will reach to a practical level [141].

It was shown that when a high voltage was applied to the outer electrode and when a smaller discharge gap was selected in the coaxial reactor, a smaller breakdown voltage was required, and therefore better NO removal could be achieved with the same high voltage. Furthermore, increasing the inner electrode diameter increased the NO removal efficiency due to the decrease in the discharge gap. Three different materials were tested for the inner electrode, and showed that tungsten had a higher NO removal efficiency than copper or stainless steel, due to a larger secondary electron emission. Copper proved more effective than stainless steel [142]. The use of a screw electrode as an inner electrode was also tested in comparison with a rod electrode, and this showed that the NO removal efficiency was higher with the screw electrode than the rod electrode, as the equivalent gap capacitance of the reactor with the screw electrode was lower. The screw electrode generates a large number of micro-discharges with a small energy deposition per micro-discharge [143], and the discharge is more intense in the screw electrode reactor, due to the higher input power when compared with the rod electrode reactor under the same applied voltage. In addition, the accidental surface of the screw electrode makes the moving gases become turbulent, increasing the probability of particle collisions and intensifying the plasma reaction. Finally, the researchers examined various dielectric materials and showed that the NO removal efficiency was higher when using corundum when compared with ceramic and quartz materials, since the relative permittivity of corundum is higher than ceramic materials. Quartz was the least effective material to be used.

In 2012, Vinh et al. [115,116] investigated the effects of different PM compositions and oxygen fraction on $NO_x$ removal efficiency in simulated exhaust gas by a dielectric barrier discharge needle-to-cylinder reactor at room temperature. They also studied the combination between a dielectric barrier discharge reactor and a wall-flow type diesel particulate filter (DPF) [144]. A diffusion flame formation system was used to produce PM [145]. The simulated gas was the combination of NO, $N_2$, $O_2$ and PM. A 50 Hz alternative high voltage supply in the range of 5–15 kV was used. It was shown that PM could increase the $NO_x$ removal efficiency intensely; however, PM was more effective when they introduced fresh PM into the reactor. For example, by using 100 mg fresh PM in a special case, the $NO_x$ removal efficiency was 28%; however, it was around 12% without using PM. They

claimed that the existence of PM inside the reactor incurs O radicals that react with HC or soot, besides other reactions. Therefore, the $NO_2$ formation process is slower and consequently, the $NO_x$ removal efficiency is higher. Accordingly, PM has worked as a reactive agent in the reactor [115]. Furthermore, the NO removal efficiency is much higher in the presence of oxygen than in the case without oxygen; however, the $NO_x$ removal efficiency is not different.

### 4.1.3. Packed bed DBD reactor

In 1999, Yamamoto et al. [102] compared two types of plasma reactors, studying reaction by-products and $NO_x$ removal efficiency. One was an ordinary packed-bed reactor without any barrier, and the other was a barrier type packed-bed plasma reactor. In addition, the effect of using $Na_2O_3$ after the plasma reactor to reduce the amount of produced $NO_2$ was studied. The $NO_2$ will react with sodium sulfite ($Na_2SO_3$) to form a non-toxic water-soluble $Na_2SO_4$ as a final product. Mok and Lee [146] in 2006 also used $Na_2SO_3$ as a reducing agent to remove sulfur dioxide and nitrogen oxides simultaneously. Ferroelectric $BaTiO_3$ pellets were used inside the reactors, with a 15 kV and 60 Hz AC power supply. A mixture of NO balanced with $N_2$ in a gas cylinder, and dry air supplied by a compressor was employed to simulate the exhaust gas. The concentrations of NO, $NO_2$, $NO_x$, CO, $CO_2$, $N_2O$, $HNO_2$ and $HNO_3$ (aqueous solution) were measured. It was shown that the hybrid system using the barrier type packed-bed plasma reactor, followed by the chemical reactor with $Na_2SO_3$, provided nearly 100% $NO_x$ removal efficiency with negligible reaction by-products of $N_2O$, CO, $HNO_2$ and $HNO_3$. It was claimed that the cost of this system was approximately 15 times more economical than the conventional selective catalyst reduction (SCR) process. The effect of reactor diameter and the optimum diameter of pellets for hybrid systems was also investigated. It was found that the $NO_2$ conversion was higher and $NO_x$ reduction was smaller for 1.5 mm diameter electrodes (the smallest size of electrode diameter considered), when compared with 5.0 mm diameter electrodes. Furthermore, 1.5 mm diameter electrodes produced less reaction by-products, such as $N_2O$, $HNO_2$, $HNO_3$ and CO, thus making this electrode most suitable for the hybrid system. In addition, the $BaTiO_3$ pellets with a diameter of 3.0 mm (the largest size considered) provided the best results on the hybrid $NO_x$ control system. The decomposition of the air alone for both different reactors was also studied, along with the effects of power supply voltage. However, the power supply frequency was not considered.

In 2011, Rajanikanth and Rout [105] studied the dielectric packed bed reactor for the removal of $NO_x$ from simulated gas, and compared this with a conventional DBD. Gas cylinders of NO in $N_2$, $N_2$, $CO_2$ and $O_2$ were used to simulate the vehicle exhaust gas at room temperature, and changes in the concentration of NO, CO, $CO_2$ and $O_2$ were also considered. Three types of catalyst were used as dielectric pellets: alumina ($Al_2O_3$), alumina coated with palladium as catalyst ($Al_2O_3$–Pd), and barium titanate ($BiTiO_3$). The voltage source for this study was a single-phase AC supply, and the range of voltage and pulse frequency of the supplier was 15–28.6 kV and 50–125 Hz, respectively. The pulse rise time was 34 ns. It was shown that the presence of a packed dielectric bed increased the discharge power. Therefore, for a given reactor size and set of operating conditions, higher NO removal efficiencies at lower voltages could be achieved. Barium titanate pellets showed better removal efficiency than the other proposed pellets. For example, DeNO was 76% for DBD alone. It was 84%, 72% and 100% for DBD with alumina, alumina coated with palladium, and barium titanate pellets, respectively. The major contribution of this paper was its comparability with conventional catalytic converters, which operate at an exhaust gas temperature around 300 °C or

above. In addition, the effects of pulse frequency and pulse voltage were also studied. It was shown that the NO removal ratio increased with an increase in the pulse repetition ratio, and an increase in the peak of applied voltage. This effect was due to the higher discharge power resulting from the higher pulse repetition rate and higher peak voltage.

In 2003, Ravi et al. [137] considered the effect of temperature on NO conversion using simulated gases consisting of NO, $O_2$, and $N_2$ in the presence of various hydrocarbons: ethylene, acetylene and n-hexane. They also studied acetylene with the presence of $H_2O$ in the simulated gas. A packed bed DBD reactor with glass beads as pellets was used. The concentration of NO and $NO_2$ was measured at different temperatures, from room temperature up to 200 °C. A 60 Hz AC high voltage was applied, ranging from 8 kV to 16 kV. It was found that the discharge power increased with increased temperature. NO conversion in the presence of ethylene and n-hexane was better than that of acetylene at all temperatures. The adding of acetylene at room temperature showed no better conversion of NO than when there were no additives. At higher temperatures, the conversion of NO was enhanced. A little enhancement in NO and $NO_x$ removal was observed in the presence of water vapor, due to the effect of OH and O radicals for NO removal.

### 4.1.4. Combined DBD reactor with catalyst or absorber

In 2003, Ravi et al. [106] investigated the conventional DBD reactor when combined with a catalytic reactor at different temperatures. Three different reactors were studied: DBD alone, catalyst alone, and a cascaded plasma catalyst reactor. The catalyst used was a commercially available SCR catalyst ($V_2O_5$–$WO_3$/$TiO_2$). The simulated gas was the composition of NO, $O_2$, and $N_2$ in the presence of ethylene and ammonia only for the cascaded reactor. A 60 Hz AC 14 kV high voltage power supply was used. It was shown that the rate of oxidation of NO to $NO_2$ decreased with temperature. In addition, it was shown that by using cascaded plasma catalyst reactors, the $NO_x$ removal efficiency was more pronounced, especially at low temperatures, and this was labeled as a "synergy effect". However, clear reasons for this synergy effect were not given. Also it was claimed that this behavior may not be common to all types of catalysts at various temperatures, and one must choose the optimal operating energy density, depending on the characteristics of the individual catalyst.

In 2004, Mok et al. [108] studied $NO_x$ removal by using a packed bed plasma reactor assisted with monolith $V_2O_5$/$TiO_2$ catalyst using AC and pulse voltage. Various effective parameters such as initial $NO_x$ concentration, gas flow rate, gas humidity and reaction temperature were studied. The simulated gas was the composition of $N_2$, $O_2$, NO balanced with $N_2$ and ethylene. It was claimed that ethylene helped NO oxidation to $NO_2$. It was shown that increasing the initial concentration of $NO_x$ decreases the removal efficiency for the same energy density; however, if the $NO_2$ fraction keeps constant, the $NO_x$ removal efficiency is similar for different initial concentrations of $NO_x$. This was an important finding in this paper that is rare in other studies. Furthermore, from their paper, it is seen that increasing the gas flow rate decreases the efficiency of $NO_x$ removal. According to the effect of water vapor, it was shown that for the plasma–catalyst system, by increasing the humidity from 0 to 3%, the $NO_x$ removal efficiency was decreased by almost 10% and further increase in humidity did not have a significant effect on $NO_x$ removal efficiency. It was also shown that for the catalyst alone reactor, increase in the reaction temperature enhances the $NO_x$ removal efficiency; however, the reaction temperature is hardly influenced by the $NO_x$ removal efficiency.

### 4.1.5. Surface plasma discharge reactor

In 2011 and 2012, Jolibois et al. [98,113] studied a wet-type reactor featuring a surface discharge. This system was studied, with a coil inserted in the electrical circuit during the treatment process, and also with a catalyst ($\gamma$-$Al_2O_3$). The simulated gas examined was a mixture of NO and air. Sodium sulfite ($Na_2SO_3$) was used to obtain the wet condition required. With wet conditions, the $NO_x$ removal efficiency is improved by dissolving $NO_2$ into the liquid as $NO^{2-}$ and $NO^{3-}$ ions [147]. However, the continuous absorption of nitrogen oxides causes saturation and acidification of the liquid, and results in the inhibition of further absorption. By adding $Na_2SO_3$, the nitrite and nitrate ions reduce to $N_2$, and therefore gas absorption is facilitated [148]. A comprehensive study was made of variations in voltage and frequency, and it was shown that the $NO_x$ removal efficiency was higher in relation to the signal frequency variations, rather than voltage variations. Furthermore, they showed that the removal efficiency was improved by inserting a coil between the power supply and the surface, and was also improved by using a catalyst. It was claimed that the inductance influenced the power consumed by the plasma.

### 4.1.6. Complex unique types of reactors

In 2009 and 2010, Matsumoto et al. [111,112] developed a new pulse generator: the nanosecond pulsed generator. This can produce 80 kV high voltage, with 2 ns rise and fall time, 5 ns pulse width and a pulse frequency of 0–100 pps. The authors claimed that this generator can achieve 100% removal efficiency. The simulated gas examined was a mixture of $N_2$ and NO. The nanosecond pulsed discharge was shown to have a distinct advantage in energy efficiency for NO removal when compared with sub-micro-second pulse discharge and other discharge methods. The effects of repetition ratio and applied voltage were studied, and it was shown that the NO removal ratio increased with an increase in the pulse repetition ratio and by increasing the peak of applied voltage due to the more discharge energy. In addition, it was shown that the positive pulse voltage gave a higher NO removal ratio than the negative pulse voltage when delivered at the same repetition rate in the case of lower applied peak voltage. On the other hand, there were no changes between the NO removal via positive and negative pulse voltage in the case of the higher applied peak voltage. Unlike previously mentioned studies, in this case, the authors studied the effects of reactor geometry. They showed that the NO removal ratio was increased by using a smaller reactor internal diameter. In addition, the NO removal ratio was increased by using a longer reactor, since the gas residence time in the reactor was also increased. Another important result of this study was that the NO removal ratio was increased considerably with the presence of $O_2$ and water fed by bubbling into the gas stream. This result demonstrated that the introduction of $O_2$ and water in this way is more effective for NO removal due to the effectiveness of the OH radicals or O radicals. In the 2010 study [112], it was shown that the nanosecond pulse discharge had more advantages than DBD and corona discharge as regards NO energy efficiency and the NO removal ratio.

In Table 3 is an overview of the papers studied, considering NTP for $NO_x$ removal from simulated gases.

### 4.2. $NO_x$ removal from diesel engines exhaust gas

### 4.2.1. Corona reactor

In 1998 and 1999, Puchkarev et al. [100,118,119] investigated the effect of a transient, non-equilibrium plasma on $NO_x$ removal. They developed a pulsed corona discharge with peak voltage of 49 kV, frequency of 1 kHz, pulse rise time of 20 ns and pulse

duration between 50 and 100 ns. They studied the effects of diameters of inner and outer electrodes, reactor length, annular dielectric inserts to prevent arcing, flow rates, pulse repetition rates, plasma volume, and pulsed and mean energy deposition into the gas on NO removal. These parameters were studied in order to determine the optimum conditions for cost effective $NO/NO_x$ removal. They showed that short pulses are more effective for efficient energy usage rather than longer pulses. In addition, the energy cost using positive corona is 1.5–2 times higher than that for negative corona for the same $NO_x$ removal. Note that the energy cost defined in this study was calculated as follows:

$$\varepsilon = \frac{250Ef}{F\Delta NO_x} \text{ (eV/molecule)} \tag{24}$$

where $\varepsilon$ is the energy cost, $E$ is the energy deposition into the gas, $f$ is the frequency and $F$ is the flow rate. $\Delta NO_x$ is the $NO_x$ removal in ppm.

The researchers realized that a high energy density generated a lower energy cost than a low energy density. They also showed that the energy cost for NO removal varied very little by varying the plasma volume. However, it changed more significantly for $NO_x$ removal. Moreover, they gave evidence that the energy cost and $NO/NO_x$ removal depended on the initial concentration of different species, such as NO, HC, particulate matter and also the gas temperature.

Koga et al. [110] compared the effect of corona discharge for $NO_x$ removal in engine exhaust gas and simulated gas. They considered a mixture of $N_2/O_2/NO/NO_2/H_2O/CO_2/C_2H_4$ as the test gas. It was shown that the $NO_x$ removal characteristics in real exhaust and simulated gas were similar if the composition were same. Effect of flow rate and residence time has been studied as well. The flow rate was changed in the range of 0.5–20 L/min. By increasing the residence time, $NO_x$ removal has been increased. Furthermore, the energy density for $NO_x$ removal depends on initial $NO_x$ concentration. When initial concentrations were 160 ppm and 24 ppm, the required energy densities for 90% $NO_x$ removal were 200 J/L and 700 J/L, respectively.

In 2007, Vinogradov et al. [128] investigated on the DC corona discharge technology for $NO_x$ removal from diesel engine exhaust. Various geometrical parameters of a rectangular corona reactor were studied in order to find the optimum parameters for the best reactor performance. A high voltage DC system with a peak voltage of 50 kV was used in this study. Comprehensive research was performed on a polarity of the corona discharge, and this showed that as regards both cleanness (mass of $NO_x$ removed relative to its initial mass), and efficiency, negative polarity is preferable. It was shown that the cleanness was almost independent of the engine load; in other words, it did not depend on the initial $NO_x$ concentration. However, the efficiency is relatively low for 0 kW and twice as high for 2.5, 4.5, and 7.5 kW diesel engines. Therefore, it was concluded that this type of corona reactor is more suitable for higher engine loads. In addition, a comprehensive study was presented of the effective parameters of the reactor, which influenced the residence time. In 2008 [129], they studied the same corona reactor, but with a pulsed discharge. It was shown in this case, that the cleanness and efficiency are independent of the polarity of the electrodes; however, the positive polarity provided a more stable discharge, and a lower concentration of ozone than negative polarity.

### 4.2.2. DBD reactor

In 2008, Rajanikanth et al. [97] studied two different types of dielectric barrier discharge reactors (wire-cylinder and pipe-cylinder) using simulated gas and real diesel engine exhaust. It was shown that, due to a shorter discharge gap, the pipe-cylinder reactor had more $NO_x$ removal efficiency than the wire-cylinder

**Table 3**
Overview of published papers featuring NTP for NO$_x$ removal from simulated gases.

| Authors | Year | Reactor type | Gas type | Catalyst/ adsorbent type | Reactor inlet temperature | Flow rate | Power generator | Peak voltage | Peak pulse frequency | The range of studied energy density |
|---|---|---|---|---|---|---|---|---|---|---|
| Mizuno et al. [79] | 1999 | DBD reactor | Simulated gas (N$_2$O/O$_2$/ N$_2$/CO$_2$/H$_2$O) | – | 20, −196 °C, −114 °C | 1–8 L/ min | Pulses generated by DC voltage supply | 30 kV | 60 Hz | – |
| Yamamoto et al. [80] | 1999 | Packed-bed DBD reactor | Simulated gas (N$_2$/NO) | BaTiO$_3$ | Room temp. | 1–2 L/ min | AC high voltage supply | 15 kV | 60 Hz | – |
| Namihira et al. [81,82] | 2000 2001 | Corona reactor | Simulated gas (NO/N$_2$/ O$_2$/H$_2$O) | – | 29.2 °C | 2–12 L/ min | Pulses generated by DC voltage supply | 49.2 kV | 13 pps | – |
| Rajanikanth and Rout [83] | 2001 | Packed-bed DBD reactor | Simulated gas (NO/N$_2$/ CO$_2$/O$_2$) | Al$_2$O$_3$, Al$_2$O$_3$–Pd, BiTiO$_3$ | Room temp. | 2 L/min | Pulses generated by DC voltage supply | 50 kV | 125 pps | 10–60 J/L |
| Ravi et al. [116] | 2003 | DBD reactor | Simulated gas (NO/N$_2$/ O$_2$/H$_2$O) | – | Room temp. and 200 °C | 2 L/min | AC high voltage supply | 16 kV | 60 Hz | 0–160 J/L |
| Ravi et al. [84] | 2003 | Combined DBD reactor with catalyst | Simulated gas (NO/NO$_2$/ O$_2$/N$_2$/ethylene, ammonia) | V$_2$O$_5$-WO$_3$/ TiO$_2$ | 100, 150 and 200 °C | 2 L/min | AC high voltage supply | 14 kV | 60 Hz | 0–160 J/L |
| Arai et al. [85] | 2004 | Corona reactor | Simulated gas (N$_2$/O$_2$/ NO) | – | – | 1 L/min | DC high voltage power supply | 15 kV | – | 0–1500 J/L |
| Saito et al. [87] | 2006 | Corona reactor | Simulated gas (N$_2$/O$_2$/ NO/H$_2$O/CO$_2$/C$_2$H$_4$) | – | – | 1 L/min | DC high voltage power supply | 15 kV | – | 0–2500 J/L |
| Matsumoto et al. [89,90] | 2009 2010 | Pulsed streamer discharge reactor | Simulated gas (N$_2$/NO) | – | – | 2 L/min | Nanosecond pulsed generator | 80 kV | 50 pps | – |
| Jolibois et al. [76] | 2012 | DBD/surface plasma reactor | Simulated gas(N$_2$/NO) | γ-Al$_2$O$_3$ | Room temp. | 1 L/min | AC high voltage supply | 20 kV | 5 kHz | 0–190 J/L |
| Wang et al. [92] | 2012 | DBD reactor | Simulated gas (N$_2$/NO) | – | – | 10 L/min | AC high voltage supply | 30 kV | 1 kHz | 100–800 J/L |
| Vinh et al. [93,94] | 2012 | DBD reactor | Simulated gas (N$_2$/NO/ O$_2$/PM) | – | Room temp. | 0.5, 1 and 2 L/min | Alternative high voltage supply | 15 kV | 50 Hz | 0–300 J/L |

reactor. The reason is the consumed power of the plasma discharge in the discharge gap which depended inversely on the gap length. They claimed that the average electric field in their pipe-cylinder reactor with 1.625 mm discharge gap is about 140 kV/cm and the corresponding electron energy is about 13 eV, which is higher than the chemical bond energy of NO (6.50 eV), NO$_2$ (3.11 eV), and CO (11.12 eV) molecules. They showed that for an energy density of higher than 30 J/L, NO removal efficiency for the pipe-cylinder is about 20–25% greater than that of the wire-cylinder reactor. However, for the NO$_x$ removal efficiency, it is almost the same after the energy density of 120 J/L. In this year, in another paper [130], they performed this experiment on cascaded plasma adsorbent and achieved the same results – the pipe-cylinder reactor had superior NO$_x$ removal efficiency when compared with the wire-cylinder reactor.

In 2011, Mohapatro et al. [132] studied a crossed flow dielectric barrier discharge reactor on the removal of NO$_x$ from a 3.75 kW diesel engine. This reactor consisted of nine electrodes with the gas flowing radially rather than axially toward the electrodes. This unique feature of the new DBD reactor improved the performance of NO$_x$ removal from diesel engine exhaust, due to the higher discharge and longer residence time. Since their results were obtained without using any catalysts/adsorbents, the authors claimed that by using a cross flow DBD reactor they could remove a significant amount of NO$_x$ from diesel engine exhaust with less energy. For example in one case, with nine electrodes, the DeNO was 100% and DeNO$_x$ was 95% with an energy efficiency of almost 3.5 g/kWh NO. However, with one electrode, the DeNO was 74% and DeNO$_x$ was 45% with an energy efficiency of almost 23.1 g/ kWh NO. The voltage source in this study was a pulse generator with a peak voltage of 25 kV and frequency of 75 pps. The pulse rise time was 20 ns and the pulse duration was 13 ms.

### 4.2.3. Packed bed DBD reactor

In 2002, Rajanikanth et al. [120] compared the results for filtered real diesel engine exhaust and simulated gas. They used a DBD reactor alone, plus a packed bed DBD reactor (a hybrid adsorber plasma reactor-HAPR) with three different molecular sieves as adsorbent beads: MS-3A, MS-4A and MS-13X. Their experiments were conducted at room temperature and also 200 °C (the average exhaust temperature in urban driving cycles). A 6 kW diesel engine was used to study the effect of different NTP reactors on filtered real diesel engine exhaust and the concentration of NO, NO$_2$, CO, CO$_2$ and aldehydes was considered during all the experiments. A single-phase AC supply with a high voltage range from 15 kV to 25 kV and a frequency of 100 pps was employed. It was claimed that the hybrid adsorber plasma reactor (HAPR) successfully demonstrated NO$_x$ removal from diesel engine exhaust. It was shown that the NO$_x$ removal efficiency when using a plasma reactor alone is 36%. This efficiency increased with the HAPR to 73% at room temperature and 78% at 200 °C. It was also determined that MS13X was the superior adsorbent for NO$_x$ removal.

In 2003, Yamamoto et al. [37] investigated the effect of non-thermal plasma on a filtered 2 kW diesel engine exhaust at different loads. Three plasma reactors were evaluated: pulse driven DBD reactor, pulse driven dielectric packed bed reactor and AC driven dielectric packed bed reactor. BaTiO$_3$ ferroelectric pellets were used for the packed bed DBD reactor. The characteristics of the power supply were a peak voltage of 25 kV, 1.2 ms pulse width, with 13.7 ns pulse rise time for the packed bed DBD reactor and 6.1 ns for the DBD reactor. The frequency of the AC supply was 60 Hz and pulse supply was 210 Hz. It was found that the AC packed-bed reactor and pelletless pulsed reactor showed better performance in terms of discharge power and NO$_x$ removal

efficiency, with minimum reaction products for a given power at no load engine. When the engine load exceeded 50%, there was only a limited decrease in NO reduction and all the reactors performed more or less equally. It is claimed that the total operating cost of the plasma-chemical hybrid system can be one-third to one-fifth of the conventional selective catalytic process. The key finding of this study is the amount of power consumption required for various configurations. Power consumption for the pulsed corona reactor without pellets is less than the pulsed corona with BaTiO$_3$ pellets, and both are less than the 60 Hz AC packed bed plasma reactor.

In 2006, Rajanikanth et al. [41] studied the injection of nitrogen radicals into the real diesel engine exhaust for the technique of NO$_x$ removal by plasma. N$_2$ gas was passed through a separate plasma reactor in order to produce N radicals which were then injected into the treatment zone. Both the NTP reactor and the reactor which produced N radicals are DBD reactors. The removal efficiency without the injection of N radicals has been compared, considering the injection of N radicals. The pulse generator was used in this study as a high voltage generator in the range of 14–25 kV, and the pulse frequency was 130 pps. It was shown that by injecting N radicals, there was quite significant improvement in NO$_x$ removal efficiency. However, the specific energy density, which is defined as the division of power to flow rate, increased considerably. It is claimed that this increment in removal efficiency without the use of catalysts or adsorbents is an important step toward NO removal by a plasma reactor alone.

In 2009, Srinivasan et al. [54] studied three different voltage energisations (AC/DC/pulse) on the removal of NO$_x$ from both filtered and unfiltered diesel engine exhaust. A packed bed DBD reactor was used, with dielectric beads. It was claimed that the performance of pulse power was better than AC and both were better than the DC energisation. The average electric field in the AC case is not as high as that observed in the pulse energized reactor or for the DC case; the average energy gained by the electrons under DC is insufficient to generate any radicals. In other words, the same removal efficiency could be achieved with less specific energy density in the pulse power than with AC power or with DC power.

### 4.2.4. Combined DBD reactor with catalyst or absorber

In 2003, Rajanikanth et al. [121] investigated a cascaded system of plasma and adsorption process for NO$_x$ and total hydrocarbon (THC) removal from a 6 kW real diesel engine's exhaust. A part of the exhaust gas was passed through a particulate filter first to filter out solid particulates and then fed to the reactors. Three different systems were evaluated: a DBD reactor, an adsorbent reactor and a cascade system. The cascade system consisted of a DBD reactor upstream of an adsorbent reactor. Three different adsorbent beads were used: activated alumina, MS-13X and activated charcoal. The concentrations of NO, NO$_2$, NO$_x$, CO, THC and aldehydes were measured at different temperatures. A high voltage AC system with a peak voltage of 25 kV and frequency of 100 pps was used in this study. It was shown that the NO$_x$ removal efficiency was higher with the plasma-associated adsorption (cascaded) process when compared with the individual processes, and the removal efficiency was found to be almost invariant in time. For example, in one special case, DeNO$_x$ was 10% for SED 52 J/L; however, for an adsorbent reactor alone, it was 14% and for a cascaded system, it was 25% for SED 52 J/L. In addition, activated charcoal and MS-13X were more effective for NO$_x$ and THC removal, respectively. It was also shown that NO$_x$ removal efficiency decreases with an increase in temperature for all the three adsorbents. However, the temperature was more effective for MS-13X and it proved less effective for the two other adsorbents. For example, with MS-

13X, the NO$_x$ removal efficiency was almost 65% at 25 °C and 45% for 140 °C.

In 2004, Rajanikanth et al. [122] again studied the cascaded plasma catalyst; however, they used a filtered diesel engine exhaust at a different load and also used SCR (V$_2$O$_5$/TiO$_2$) as a catalyst. It was shown that the NO removal efficiency decreased with an increase in exhaust temperature. In addition, the DeNO decreased when increasing the engine load, due to an increase in the initial concentration of NO. They showed that with the catalyst alone under 200 °C, NO$_x$ removal was not affected. However, the plasma-assisted catalytic reactor was successfully employed to remove NO$_x$ from diesel engine exhaust at different loads of the engine. In one particular instance, the NO$_x$ removal efficiency was 33%, 27% and 87% respectively for a plasma reactor, a catalyst reactor and a plasma-assisted catalyst reactor.

In 2007, Rajanikanth et al. [125] performed the same experiment as [96] (cited previously), but this time in a more detailed fashion. The researchers examined a plasma reactor with an adsorbent and then a catalyst reactor, while using different kinds of adsorbent and catalyst materials. They showed that between three different adsorbent materials (activated charcoal, MS-13X, activated alumina), the activated charcoal cascaded with plasma, exhibited superior adsorption properties. Furthermore, MS-13X cascaded with plasma gave higher NO$_x$ removal efficiency when compared to activated alumina cascaded with plasma. It was shown that the performance of the cascaded process at high temperatures was poorer than that at room temperature, due to the poor performance of plasma and adsorbent processes at higher temperatures. A four-stage cascaded plasma catalyst was also examined. When comparing the four-stage cascaded plasma catalyst with the two-stage model, the four-stage catalyst showed superior performance. It was claimed that the cascaded plasma-adsorbent reactor could be a viable option for low temperature ( < 200 °C) stationary diesel exhaust NO$_x$ treatment. However, the cascaded plasma-activated catalytic reactor could also be a better option for non-stationary diesel exhaust NO$_x$ treatment, since it is not significantly affected by the plasma reactor temperature.

In 2009, Rajanikanth et al. [131] presented a novel way for generating high voltage for the plasma reactor in diesel engine exhaust. A solar powered high frequency electric discharge was developed to improve the size and specific energy density required in comparison with the traditional repetitive pulse or AC energisation. This generator can produce up to 16 kV high voltage with a high frequency of 12.2 kHz and a pulse rise time of 24 ns. This new high voltage generator was employed with DBD reactors, and different systems were examined, such as cascaded plasma-adsorbent and cascaded plasma–catalyst reactors. It was shown that under this solar-powered high-frequency AC application, there was a considerable improvement in the NO$_x$ removal, when compared with other generators. For example, in the DBD reactor, NO$_x$ removal efficiency was 22%, 27% and 46% respectively for the 50 Hz ordinary AC power supply, repetitive pulse power supply and 12.2 kHz AC power supply energized by a solar powered battery. In addition, the cascaded system of

**Table 4**
Initial concentrations of the main substances in diesel engine exhaust.

| Substance | Concentration (ppm) or volume fraction (%) |
|---|---|
| O$_2$ | 12.5% |
| CO$_2$ | 4.9% |
| CO | 1770 ppm |
| NO | 600 ppm |
| NO$_2$ | 66 ppm |
| NO$_x$ (NO+NO$_2$) | 666 ppm |

**Table 5**
Overview of the published papers considering NTP for $NO_x$ removal from diesel engine exhaust.

| Authors | Year | Reactor type | Gas type | Catalyst/adsorbent type | Reactor temperature | Flow rate | Power generator | Peak voltage | Peak pulse frequency | The range of studied energy density |
|---|---|---|---|---|---|---|---|---|---|---|
| Puchkarev et al. [78,96,97] | 1998 1999 | Corona reactor | Diesel exhaust gas | – | – | 1–10 L/min | Pulse supply | 49 kV | 1 kHz | – |
| Rajanikanth and Ravi [98] | 2002 | DBD reactor/ Combined DBD reactor with adsorbent | Simulated gas (NO in $N_2$, $O_2$, CO)/diesel engine exhaust at no load | MS-3A, MS-4A, MS-13X | Room temp. and 200 °C | 2 L/min | AC high voltage supply | 25 kV | 100 pps | – |
| Yamamoto et al. [99] | 2003 | DBD reactor/Packed bed DBD reactor | Diesel engine exhaust at various loads | $BaTiO_3$ | Room temp. | 3 L/min | AC high voltage supply/ pulse supply | 25 kV | 60 Hz for AC/ 210 Hz for pulse | – |
| Rajanikanth et al. [100] | 2003 | DBD reactor/ Combined DBD reactor with adsorbent | Diesel engine exhaust at no load and load 50% | Activated alumina, MS-13X, activated charcoal | Room temp. | 2 L/min | AC high voltage supply | 25 kV | 100 pps | 0–100 J/L |
| Rajanikanth and Ravi [101] | 2004 | DBD reactor/ Combined DBD reactor with catalyst | Diesel engine exhaust at various loads | SCR ($V_2O_5/TiO_2$) | 100, 150 and 200 °C | 2 L/min | Pulse supply | – | 80 pps | 0–100 J/L |
| Rajanikanth et al. [74,102,105,106] | 2004 2005 2007 | DBD reactor/ Combined DBD reactor with catalyst and adsorbent | | | DBD reactor/ Combined DBD reactor with catalyst and adsorbent | Diesel engine exhaust at various loads | Adsorbent: activated charcoal, molecular sieves MS-13X, activated alumina/ catalyst: conventional 2-way and 3-way catalyst, non-conventional activated alumina ($Al_2O_3$) | 24, 100, 150 °C | 4 L/min | AC high voltage supply |
| | | | | | | | | 25 kV | 130 pps | 0–100 J/L |
| Rajanikanth and Sushma [103] | 2006 | DBD reactor/ Combined DBD reactor with adsorbent | Diesel engine exhaust at various loads | $BaTiO_3$ | Room temp. | 4 L/min | Pulse generator | 25 kV | 130 pps | – |
| Koga et al. [88] | 2006 | Corona reactor | engine exhaust gas and Simulated gas ($N_2$/$O_2$/NO/$NO_2$/$H_2O$/$CO_2$/$C_2H_4$) | – | – | 0.5–20 L/min | DC high voltage power supply | 15 kV | – | 0–2500 J/L |
| Rajanikanth and Srinivasan [104] | 2007 | DBD reactor/ Combined DBD reactor with catalyst and adsorbent | Diesel engine exhaust at various loads | Adsorbent: activated charcoal, molecular sieves MS-13X, activated alumina/catalyst: alumina | 24, 100, 150 °C | 4 L/min | AC high voltage supply | 25 kV | 130 pps | 0–100 J/L |
| Vinogradov et al. [107,108] | 2007 2008 | Corona reactor | Diesel engine exhaust | – | 25 °C | 8 L/min | DC high voltage supply/ pulse supply | 50 kV | 1000 Hz | 0–140 J/L |
| | 2008 | DBD reactor/ Combined DBD | diesel engine exhaust at various loads and | MS-13X/carbon molecular sieves (CMS)/activated charcoal | Room temp. | 2 L/min | Pulse supply | 25 kV | 130 pps | 0–190 J/L |

**Table 5** (continued)

| Authors | Year | Reactor type | Catalyst/adsorbent type | Gas type | Reactor temperature | Flow rate | Power generator | Peak voltage | Peak pulse frequency | The range of studied energy density |
|---|---|---|---|---|---|---|---|---|---|---|
| Rajanikanth and Sinha [75,109] | | reactor with adsorbent | – | Simulated gas (NO/N$_2$, O$_2$), | Room temp. | 2 L/min | DC/AC high voltage supply/pulse supply | 25 kV | 130 pps | 0–190 J/L |
| Srinivasan et al. [46] | 2009 | Packed bed DBD reactor | – | Diesel engine exhaust at various loads | Room temp. | 2–4 L/min | AC high voltage supply/AC high voltage supply (solar powered battery)/pulse supply | 16 kV for AC, 25 kV for pulse | 50 Hz for AC, 12.2 kHz for AC (solar), 87 pps for pulse | 90 J/L |
| Rajanikanth et al. [110] | 2009 | DBD reactor/Combined DBD reactor with catalyst | Commercially available catalytic converter | Diesel engine exhaust at various loads | | | | | | |
| Mohapatro et al. [111] | 2011 | Cross-flow DBD reactor | – | Diesel engine exhaust at load 27% | – | 2–25 L/min | Pulse supply | 20 kV | 75 pps | 0–550 J/L |

a solar-powered generator with adsorbent had superior performance when compared with other systems. It was claimed that this solar-powered high voltage power supply could be designed for a possible retrofit in vehicles. It could be used on top of a vehicle with appropriate mechanical fixtures. However, it would need modification to the reactor and the plasma in order to accommodate the actual exhaust flow-rate and temperature.

### 4.2.5. Effect of carbonaceous soot oxidation on NO$_x$ removal

Rajanikanth et al. [96,97,123,126,127] studied the effect of carbonaceous soot oxidation on NO$_x$ removal. They used unfiltered diesel engine exhaust which contains carbonaceous soot, and measured the concentration of CO$_2$, CO, NO, NO$_2$, THC and aldehydes. They were compared using six different reduction systems: a DBD alone, an adsorbent alone, a cascaded plasma-adsorbent reactor (PRAR), a pellet bed catalyst reactor, a honeycomb catalyst reactor and a cascaded plasma-catalytic reactor (PRCR). A high voltage AC system with a peak voltage of 25 kV and a frequency of 130 pps was employed on a 4.4 kW diesel engine exhaust at no load condition. Three different temperatures were examined: 24 °C, 100 °C and 150 °C.

It was shown that the NO$_x$ removal efficiency using the plasma technique was improved with the presence of carbonaceous soot in the diesel engine raw exhaust gas, due to the reactions with NO$_2$. Taking as an example one case, for a specific energy of 50 J/L, NO$_x$ removal efficiency was 45% for an unfiltered diesel engine; however, DeNO$_x$ was 30% for filtered diesel exhaust gas [96]. In Table 4, the initial concentrations of the main substances in a diesel engine exhaust that participate in plasma NO$_x$ removal for a 2.6 kW diesel engine at 40% load, have been tabulated [97,130].

In addition, different adsorbent beads were tested, such as activated charcoal, molecular sieves, MS-13X and activated alumina. Adsorbent reactor alone and PRAR approved to show good performance in NO$_x$ removal; however, they did not exhibit efficient CO removal. They used various catalysts, such as conventional two-way and three-way catalysts, but only studied CO removal with the catalyst reactor. It was shown that generally, catalysts have a positive effect on CO removal. Although the two-way catalyst exhibits a more effective CO removal than the three-way catalyst, the problem is that the catalyst did not show effective results on NO$_x$ removal, due to a high oxidizing environment in the diesel engine exhaust.

In Table 5, an overview of the studies considering NTP for NO$_x$ removal from diesel engine exhaust is schematized.

## 5. Conclusion

As presented in this review, non-thermal plasma has been shown to have promising potential for the removal of NO$_x$ from exhaust gases. Many studies have been conducted in order to improve the existing technologies and to develop new ways to increase the performance of NTP. Various combinations of NTP with catalyst and adsorbent have also been initiated in order to increase the NO$_x$ removal efficiency. Study of the published papers indicates that pulse power technology is more efficient for generating plasma, and has increasingly been applied in recent years. Furthermore, combining NTP with a catalyst or adsorber while using a packed bed reactor, can be more effective than NTP alone. The NO$_x$ removal efficiency from the exhaust gas in a diesel engine is higher than simulated gases, due to the presence of carbonaceous soot in the emission gas. Most of the presented studies do not cover beyond a laboratory scale. There are also some contradictions in some aspects of NTP, such as what polarity is optimum for NO$_x$ removal. Regarding the existing publications, energy consumption is the main challenge of using this technology. More comprehensive research should be

considered in order to improve the electrical aspects and also the reactor design. Additionally, a few studies investigated the economics of NTP technology. In view of global health and environmental concerns and increasingly stringent emission regulation restrictions, NTP technology is predicted to become commercially viable in the future, and therefore, more research is necessary in order to make this technology widely available.

# References

[1] Guibet JC, Faure-Birchem E. Fuels and engines: technology, energy. Environment. Éditions Technip; 1999 ISBN: 2710807513, 9782710807513, Publications of the French Petroleum Institute, http://books.google.com/books/about/Fuels_and_engines.html?id=bW8nAQAAMAAJ.

[2] Holzer F, Roland U, Kopinke FD. Combination of non-thermal plasma and heterogeneous catalysis for oxidation of volatile organic compounds: Part 1. Accessibility of the intra-particle volume. Appl Catal B Environ 2002;38:163–81.

[3] Roland U, Holzer F, Kopinke FD. Combination of non-thermal plasma and heterogeneous catalysis for oxidation of volatile organic compounds: Part 2. Ozone decomposition and deactivation of $\gamma$-$Al_2O_3$. Appl Catal B Environ 2005;58:217–26.

[4] Roland U, Holzer F, Pöppl A, Kopinke FD. Combination of non-thermal plasma and heterogeneous catalysis for oxidation of volatile organic compounds: Part 3. Electron paramagnetic resonance (EPR) studies of plasma-treated porous alumina. Appl Catal B Environ 2005;58:227–34.

[5] Subrahmanyam C, Magureanu M, Renken A, Kiwi-Minsker L. Catalytic abatement of volatile organic compounds assisted by non-thermal plasma: Part 1. A novel dielectric barrier discharge reactor containing catalytic electrode. Appl Catal B Environ 2006;65:150–6.

[6] Subrahmanyam C, Renken A, Kiwi-Minsker L. Catalytic abatement of volatile organic compounds assisted by non-thermal plasma: Part II. Optimized catalytic electrode and operating conditions. Appl Catal B Environ 2006;65:157–62.

[7] Gu W, Yu H, Liu W, Zhu J, Xu X. Demand response and economic dispatch of power systems considering large-scale plug-in hybrid electric vehicles/electric vehicles (PHEVs/EVs): a review. Energies 2013;6:4394–417.

[8] Schuetzle D, Hammerle R. Fundamentals and applications of chemical sensors. American Chemical Society; 1986 ISBN13: 9780841209732, ACS publications (American Chemical Society), http://pubs.acs.org/isbn/9780841209732.

[9] Stratakis GA. Experimental investigation of catalytic soot oxidation and pressure drop characteristics in wall flow diesel particulate filters. ([PhD thesis]). Greece: University of Thessaly; 2004.

[10] Jelles SJ. Development of catalytic systems for diesel particulate oxidation. ([PhD thesis]). Delft University of Technology; 1999.

[11] Prasad R, Rao Bella V. A review on diesel soot emission, its effect and control. Bull Chem React Eng Catal 2010;5:69–86.

[12] Skalska K, Miller JS, Ledakowicz S. Trends in $NO_x$ abatement: a review. Sci Total Environ 2010;408:3976–89.

[13] Riess J. $NO_x$: how nitrogen oxides affect the way we live and breathe. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards; 1998.

[14] Gómez-García MA, Pitchon V, Kiennemann A. Pollution by nitrogen oxides: an approach to $NO_x$ abatement by using sorbing catalytic materials. Environ Int 2005;31:445–67.

[15] Chaloulakou A, Mavroidis I, Gavriil I. Compliance with the annual $NO_2$ air quality standard in Athens. Required $NO_x$ levels an expected health implications. Atmos Environ 2008;42:454–65.

[16] Sher E. Handbook of air pollution from internal combustion engines. Academic Press; 1998 ISBN: 0-12-6398554-0, United States of America, https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=0CBwQFjAA&url=http%3A%2F%2Ffh-zwickau.de%2Ffileadmin%2Fugroups%2Fftz%2Fftz%2Fmitglied_stan%2Fverbrennungsmotoren%2FSher.pdf&ei=qIztU4zcHsHB7AavvIHoBg&usg=AFQjCNEjOvgHESFzhLc2dt3I1DsM-AAB5yQ&sig2=v_whAuNwmGgF2nXMkRyVow&bvm=bv.73231344,d.bGE.

[17] Devahasdin S, Fan Jr C, Li K, Chen DH. $TiO_2$ photocatalytic oxidation of nitric oxide: transient behavior and reaction kinetics. J Photochem Photobiol: Chem 2003;156:161–70.

[18] Tunnicliffe W, Burge P, Ayres J. Effect of domestic concentrations of nitrogen dioxide on airway responses to inhaled allergen in asthmatic patients. Lancet 1994;344:1733–6.

[19] Koenig JQ. Health effects of nitrogen dioxide, (Book title:Health effects of ambient air pollution). Springer; 2000; 165–80, ISBN: 978-1-4615-4569-9, Kluwer Academic publishers, Germany.

[20] Likens GE, Bormann FH, Johnson NM. Acid rain. Environ Sci Policy Sustain Dev 1972;14:33–40.

[21] Pauleta SR, Dell'Acqua S, Moura I. Nitrous oxide reductase. Coord Chem Rev 2013;257:332–49.

[22] Smith K. The potential for feedback effects induced by global warming on emissions of nitrous oxide by soils. Glob Change Biol 1997;3:327–38.

[23] Yagiela JA. Health hazards and nitrous oxide: a time for reappraisal. Anesth Prog 1991;38:1–11.

[24] Panel NRCDISCHE. Health effects of exposure to diesel exhaust: the report of the health effects panel of the diesel impacts study committee, National Research Council: National Academy of Sciences; 1981.

[25] Hariri MH. Nitrogen oxides as atmospheric pollutants: $NO_x$ removal in the presence of oxygen with metal oxides. Sci Iran 1994;1:257–66.

[26] Van Setten BAAL, Makkee M, Moulijn JA. Catalytic diesel particulate filters reduce the in vitroestrogenic activity of diesel exhaust. Catal Rev 2001;43:489–564.

[27] Heeb, Norbert V, Saxer, Christian J, Forss, Anna-Maria, Brühlmann, Stefan. Trends of $NO^-$, $NO^{2-}$, and $NH^{3-}$ emission from gasoline-fueled Euro-3 to Euro-4 passenger cars. Atmos Environ 2008;42:2543–54.

[28] Prasad R, Venkateswara RB. A review on diesel soot emission, its effect and control; 2010.

[29] Johnson TV. Diesel emission control in review. US Department of Energy Diesel Engine Efficiency and Emissions Reduction (DEER) Conference; 2006.

[30] Johnson TV. Review of diesel emissions and control. Int J Engine Res 2009;10:275–85.

[31] Narula CK, Daw CS, Hoard JW, Hammer T. Materials issues related to catalysts for treatment of diesel exhaust. Int J Appl Ceram Technol 2005;2:452–66.

[32] Meloni R, Naso V. An insight into the effect of advanced injection strategies on pollutant emissions of a heavy-duty diesel engine. Energies 2013;6:4331–51.

[33] Jeong K, Lee D, Park S, Lee CS. Effect of two-stage fuel injection parameters on $NO_x$ reduction characteristics in a DI diesel engine. Energies 2011;4:2049–60.

[34] Gieshoff J, Pfeifer M, Schäfer-Sindlinger A, Spurk PC, Garr G, Leprince T, et al. Advanced urea SCR catalysts for automotive applications, SAE technical paper; 2001.

[35] Radojevic M. Reduction of nitrogen oxides in flue gases. Environ Pollut 1998;102:685–9.

[36] Tayyeb Javed M, Irfan N, Gibbs BM. Control of combustion-generated nitrogen oxides by selective non-catalytic reduction. J Environ Manag 2007;83:251–89.

[37] Yamamoto T, Rajanikanth BS, Okubo M, Kuroki T, Nishino M. Performance evaluation of nonthermal plasma reactors for NO oxidation in diesel engine exhaust gas treatment. IEEE Trans Ind Appl 2003;39:1608–13.

[38] Palash SM, Kalam MA, Masjuki HH, Masum B, Rizwanul Fattah I, Mofijur M. Impacts of biodiesel combustion on $NO_x$ emissions and their reduction approaches. Renew Sustain Energy Rev 2013;23:473–90.

[39] Huttunen JT, Alm J, Liikanen A, Juutinen S, Larmola T, Hammar T, et al. Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions. Chemosphere 2003;52:609–21.

[40] Iglesias-Juez A, Hungría A, Martínez-Arias A, Fuerte A, Fernández-García M, Anderson J, et al. Nature and catalytic role of active silver species in the lean $NO_x$ reduction with $C_3 < H < 6 <$ in the presence of water. J Catal 2003;217:310–23.

[41] He X, Meng M, He J, Zou Z, Li X, Li Z, et al. A potential substitution of noble metal Pt by perovskite $LaCOO_3$ in $ZrTiO_4$ supported lean-burn $NO_x$ trap catalysts. Catal Commun 2010;12:165–8.

[42] West B, Huff S, Parks J, Lewis S, Choi J-S, Partridge W, et al. Assessing reductant chemistry during in-cylinder regeneration of diesel lean $NO_x$ traps. SAE technical paper; 2004. p. 3023.

[43] Han Z, Uludogan A, Hampson GJ, Reitz RD. Mechanism of soot and $NO_x$ emission reduction using multiple-injection in a diesel engine. SAE Trans 1996;105:837–52.

[44] Bhatt NM, Rathod PP, Sorathiya AS, Patel R. Effect of multiple injections on the performance and emission of diesel engine: a review study, 2013, International Journal of Emerging Technology and Advanced Engineering, 3(3),134-140, http://www.ijetae.com/files/Volume3Issue3/IJETAE_0313_21.pdf.

[45] Gomez E, Rani DA, Cheeseman CR, Deegan D, Wise M, Boccaccini AR. Thermal plasma technology for the treatment of wastes: a critical review. J Hazard Mater 2009;161:614–26.

[46] Plasma exhaust treatment. Dieselnet; 2000.

[47] Tonks L, Langmuir I. Oscillations in ionized gases. Phys Rev 1929;vol. 33.

[48] Tendero C, Tixier C, Tristant P, Desmaison J, Leprince P. Atmospheric pressure plasmas: a review. Spectrochim Acta Part B: Atom Spectrosc 2006;61:2–30.

[49] Auciello O, Flamm DL. Plasma diagnostics: discharge parameters and chemistry. ISBN-10: 0120676354, the University of Michigan, Academic Press, Elsevier, United States; 1989, http://books.google.com/books/about/Plasma_Diagnostics_Discharge_parameters.html?id=kjBRAAAAMAAJ.

[50] Fridman A. Plasma chemistry. ISBN: 9781107684935, Cambridge University Press, England; 2008.

[51] Kogelschatz U, Eliasson B, Egli W. From ozone generators to flat television screens: history and future potential of dielectric-barrier discharges. Pure Appl Chem 1999;71:1819–28.

[52] Yao S, Madokoro K, Fushimi C, Fujioka Y. Experimental investigation on diesel PM removal using uneven DBD reactors. AIChE J 2007;53:1891–7.

[53] Jaffré Y-N, Aka-Ngnui T, Beroual A. Non-thermal plasmas for $NO_x$ treatment. In: Proceedings of the 2nd international multi-conference on engineering and technological innovation; 2009.

[54] Srinivasan AD, Rajanikanth BS, Mahapatro S. Corona treatment for $NO_x$ reduction from stationary diesel engine exhaust impact of nature of

energization and exhaust composition; 2009, Electrostatics Joint Conference, Boston University, June 16-18, p1.26.

[55] Winands GJJ. Efficient streamer plasma generator. ([PhD thesis]). Technische Universiteit Eindhoven; 2007.

[56] Ahlfont K, Sandborgh H. Pulsed power technology and applications – Scandinavia. 1999.

[57] Akiyama H, Sakugawa T, Namihira T, Takaki K, Minamitani Y, Shimomura N. Industrial applications of pulsed power technology. Dielectr Electr Insul IEEE Trans 2007;14:1051–64.

[58] Xu D-Y, et al. Three-dimensional modelling of the characteristics of long laminar plasma jets with lateral injection of carrier gas and particulate matter. J Phys D Appl Phys 2003;36:1583.

[59] Yao S. Plasma reactors for diesel particulate matter removal. Recent Pat Chem Eng 2009;2:67–75.

[60] Takaki K, Katsuki S. Industrial applications of pulsed power technology. IEEE Trans Fundam Mater 2009;129:62–5.

[61] Mueller G, An W, Berghofer T, DelGiacco M, Eing C, Fetzer R, et al. Status and recent progress in pulsed power applications at Karlsruhe Institute of Technology (KIT). Pulsed Power Conference (PPC); 2011 IEEE 2011. pp. 46–102.

[62] Babaie M, Davari P, Zare F, Rahman MM, Rahimzadeh H, Ristovski Z. Effect of pulsed power on particle matter in diesel engine exhaust using a DBD plasma reactor. IEEE Trans Plasma Sci 2013;41:2349–58.

[63] Penetrante BM. Non-thermal plasma techniques for pollution control: Part A: overview, fundamentals and supporting technologies. Part B: electron beam and electrical discharge processing. Berlin, Germany: Springer Verlag; 1994.

[64] Penetrante BM, Brusasco RM, Merritt BT, Vogtlin GE. Environmental applications of low-temperature plasmas. Pure Appl Chem 1999;71:1829–35.

[65] Radoiu MT. Studies on atmospheric plasma abatement of PFCs. Radiat Phys Chem 2004;69:113–20.

[66] Chang J-S, Lawless PA, Yamamoto T. Corona discharge processes. Plasma Sci IEEE Trans 1991;19:1152–66.

[67] Kim HH. Nonthermal plasma processing for air-pollution control: a historical review, current issues, and future prospects. Plasma Process Polym 2004;1:91–110.

[68] Vandenbroucke AM, Morent R, De Geyter N, Leys C. Non-thermal plasmas for non-catalytic and catalytic VOC abatement. J. Hazard Mater 2011;195:30–54.

[69] Chmielewski AG, Iller E, Tyminski B, Zimek Z, Licki J. Flue gas treatment by electron beam technology. Mod Power Syst 2001;5:54–8.

[70] Bhasavanich D, Ashby S, Deeney C, Schlitt L. Flue gas irradiation using pulsed corona and pulsed electron beam technology. In: Proceedings of the 9th IEEE international pulsed power conference, digest of technical papers; 1993. p. 441–4.

[71] Penetrante B, Hsiao M, Bardsley J, Merritt B, Vogtlin G, Wallman P, et al. Electron beam and pulsed corona processing of carbon tetrachloride in atmospheric pressure gas streams. Phys Lett A 1995;209:69–77.

[72] Chang J, Urashima K. Removal of volatile organic compounds from air streams and industrial flue gases by non-thermal plasma technology. IEEE Trans Dialectr Electr Insul 2000;7:602–14.

[73] Whealton JH, Hansen GR, Storey JM, Raridon RJ, Armfield JS, Bigelow TS, et al. Non-thermal plasma exhaust aftertreatment: a fast rise-time concept. SAE; 1997.

[74] McAdams R. Prospects for non-thermal atmospheric plasmas for pollution abatement. J Phys D Appl Phys 2001;34:2810.

[75] Fridman A, Chirokov A, Gutsol A. Non-thermal atmospheric pressure discharges. J Phys D Appl Phys 2005;38:R1.

[76] Kogelschatz U. Dielectric-barrier discharges: their history, discharge physics, and industrial applications. Plasma Chem Plasma Process 2003;23:1–46.

[77] Wang C, Zhang G, Wang X. Comparisons of discharge characteristics of a dielectric barrier discharge with different electrode structures. Vacuum 2011;86(7):960–4.

[78] Tudor V, Ohadi M, Salehi M, Lawler J. Advances in control of frost on evaporator coils with an applied electric field. Int J Heat Mass Transf 2005;48:4428–34.

[79] Eliasson B, Hirth M, Kogelschatz U. Ozone synthesis from oxygen in dielectric barrier discharges. J Phys D Appl Phys 1987;20:1421.

[80] Fang Z, Qiu Y, Zhang C, Kuffel E. Factors influencing the existence of the homogeneous dielectric barrier discharge in air at atmospheric pressure. J Phys D Appl Phys 2007;40:1401.

[81] Mizuno A. Industrial applications of atmospheric non-thermal plasma in environmental remediation. Plasma Phys Control Fusion 2007;49:A1.

[82] Chen HL, Lee HM, Chen SH, Chao Y, Chang MB. Review of plasma catalysis on hydrocarbon reforming for hydrogen production – interaction, integration, and prospects. Appl Catal B Environ 2008;85:1–9.

[83] Futamura S, Einaga H, Zhang A. Comparison of reactor performance in the nonthermal plasma chemical processing of hazardous air pollutants. Ind Appl IEEE Trans 2001;37:978–85.

[84] Penetrante BM, Hsiao MC, Merritt BT, Vogtlin GE, Wallman PH. Comparison of electrical discharge techniques for nonthermal plasma processing of NO in $N_2$. Plasma Sci IEEE Trans 1995;23:679–87.

[85] Penetrante B, Hsiao M, Merritt B, Vogtlin G, Wallman P, Neiger M, et al. Pulsed corona and dielectric–barrier discharge processing of NO in $N_2$. Appl Phys Lett 1996;68:3719–21.

[86] Malik MA, Kolb JF, Sun Y, Schoenbach KH. Comparative study of NO removal in surface-plasma and volume-plasma reactors based on pulsed corona discharges. J Hazard Mater 2011;197:220–8.

[87] Kim H-H, Oh S-M, Ogata A, Futamura S. Decomposition of gas-phase benzene using plasma-driven catalyst (PDC) reactor packed with Ag/TiO₂ catalyst. Appl Catal B Environ 2005;56:213–20.

[88] Roy S, Baiker A. $NO_x$ storage-reduction catalysis: from mechanism and materials properties to storage-reduction performance. Chem Rev 2009;109:4054–91.

[89] Roy S, Hegde MS, Madras G. Catalysis for $NO_x$ abatement. Appl Energy 2009;86:2283–97.

[90] Epling WS, Campbell LE, Yezerets A, Currier NW, Parks JE. Overview of the fundamental reactions and degradation mechanisms of $NO_x$ storage/reduction catalysts. Catal Rev 2004;46:163–245.

[91] Atkinson R, Baulch DL, Cox RA, Hampson JRF, Kerr JA, Troe J. Evaluated kinetic and photochemical data for atmospheric chemistry. J Phys Chem Ref 1989;18:S881–1097.

[92] Kossyi IA, Kostinsky AY, Matveyev AA, Silakov VP. Kinetic scheme of the non-equilibrium discharge in nitrogen–oxygen mixtures. Plasma Sources Sci Technol 1992;1:207–20.

[93] Atkinson R, Baulch DL, Cox RA, Hampson JRF, Kerr JA, Rossi MJ, et al. Evaluated kinetic and photochemical data for atmospheric chemistry. J Phys Chem Ref 1997:S1329–499.

[94] Sathiamoorthy G, Kalyana S, Finney WC, Clark RJ, Locke BR. Chemical reaction kinetics and reactor modeling of $NO_x$ removal in a pulsed streamer corona discharge reactor. Ind Eng Chem Res 1999;38:1844–55.

[95] Zhao G-B, Hu X, Yeung M-C, Plumb OA, Radosz M. Nonthermal plasma reactions of dilute nitrogen oxide mixtures: $NO_x$ in nitrogen. Ind Eng Chem Res 2004;43:2315–23.

[96] Rajanikanth BS, Das S, Srinivasan AD. Unfiltered diesel engine exhaust treatment by discharge plasma: effect of soot oxidation. Plasma Sci Technol 2004;6:2475–80.

[97] Rajanikanth BS, Sinha D. Achieving better $NO_x$ removal in discharge plasma reactor by field enhancement. Plasma Sci Technol 2008;10:198–202.

[98] Jolibois J, Takashima K, Mizuno A. Application of a non-thermal surface plasma discharge in wet condition for gas exhaust treatment: $NO_x$ removal. J Electrostat 2012;70:300–8.

[99] Hoard J, Balmer M. Analysis of plasma-catalysis for diesel $NO_x$ remediation. SAE technical paper; 1998.

[100] Puchkarev V, Kharlov A, Gundersen M, Roth G. Application of pulsed corona discharge to diesel exhaust remediation. In: Proceedings of the 12th IEEE international pulsed power conference, digest of technical papers, vol. 1; 1999. p. 511–4.

[101] Mizuno A, Rajanikanth BS, Shimizu K, Kinoshita K, Yanagihara K, Okumoto M, et al. Non-thermal plasma applications at very low temperature. Combust Sci Technol 1998;133:49–63.

[102] Yamamoto T, Okubo M, Hayakawa K, Kitaura K. Towards ideal $NO_x$ control technology using plasma-chemical hybrid process. Phoenix, AZ, USA: IEEE; 1999; 1495–502.

[103] Namihira T, Tsukamoto S, Douyan W, Katsuki S, Hackam R, Akiyama H, et al. Improvement of $NO_x$ removal efficiency using short-width pulsed power. IEEE Trans Plasma Sci 2000;28:434–42.

[104] Namihira T, Tsukamoto S, Wang D, Hori H, Katsuki S, Hackam R, et al. Influence of gas flow rate and reactor length on NO removal using pulsed power. IEEE Trans Plasma Sci 2001;29:592–8.

[105] Rajanikanth BS, Rout S. Studies on nitric oxide removal in simulated gas compositions under plasma-dielectric/catalytic discharges. Fuel Process Technol 2001;74:177–95.

[106] Ravi V, Mok YS, Rajanikanth BS, Kang HC. Studies on nitrogen oxides removal using plasma assisted catalytic reactor. Plasma Sci Technol 2003;5:2057–62.

[107] Arai M, Saito M, Yoshinaga S. Effect of oxygen on nox removal in corona discharge field: $NO_x$ behavior without a reducing agent. Combust Sci Technol 2004;176:1653–65.

[108] Mok YS, Koh DJ, Shin DN, Kim KT. Reduction of nitrogen oxides from simulated exhaust gas by using plasma–catalytic process. Fuel Process Technol 2004;86:303–17.

[109] Saito M, Koga H, Yoshinaga S, Arai M. Effect of coexisting gases on NO removal using corona discharge. JSME Int J Ser B Fluids Therm Eng 2006;49:1282–9.

[110] Koga H, Saito M, Arai M. NO removal from exhaust gas in a corona discharge field. Rev Automot Eng 2006;27:61–7.

[111] Matsumoto T, Wang D, Namihira T, Akiyama H. Exhaust gas treatment using nano seconds pulsed discharge. In: Proceedings of pulsed power conference, 2009 PPC '09 IEEE2009. p. 1035–40.

[112] Matsumoto T, Wang D, Namihira T, Akiyama H. Energy efficiency improvement of nitric oxide treatment using nanosecond pulsed discharge. IEEE Trans Plasma Sci 2010;38:2639–43.

[113] Jolibois J, Takashima K, Mizuno A. $NO_x$ removal using a wet type plasma reactor based on a three-electrode device. J Phys: Conf Ser 2011;301.

[114] Wang T, Sun B-M, Xiao H-P, Zeng J-Y, Duan E-P, Xin J, et al. Effect of reactor structure in DBD for nonthermal plasma processing of NO in $N_2$ at ambient temperature. Plasma Chem Plasma Process 2012;32(6):1189–201.

[115] Vinh T, Watanabe S, Furuhata T, Arai M. Fundamental study of $NO_x$ removal from diesel exhaust gas by dielectric barrier discharge reactor. J Mech Sci Technol 2012;26:1921–8.

[116] Vinh TQ, Watanabe S, Furuhata T, Arai M. Effects of particulate matter on $NO_x$ removal in dielectric barrier discharges. J Energy Inst 2012;85:163–9.

[117] Ravi V, Mok YS, Rajanikanth BS, Kang H-C. Temperature effect on hydrocarbon-enhanced nitric oxide conversion using a dielectric barrier discharge reactor. Fuel Process Technol 2003;81:187–99.

[118] Puchkarev V, Roth G, Gundersen M. Plasma processing of diesel exhaust by pulsed corona discharge. SAE technical paper; 1998.

[119] Slone R, Ramavajjala M, Palekar V, Puchkarev V. Pulsed corona plasma technology for the removal of NO, from diesel exhaust. SAE technical paper; 1998.

[120] Rajanikanth BS, Ravi V. Removal of nitrogen oxides in diesel engine exhaust by plasma assisted molecular sieves. Plasma Sci Technol 2002;4:1399–406.

[121] Rajanikanth BS, Srinivasan AD, Nandiny BA. A cascaded discharge plasma-adsorbent technique for engine exhaust treatment. Plasma Sci Technol 2003;5:1825–33.

[122] Rajanikanth BS, Ravi V. DeNO$_x$ study in diesel engine exhaust using barrier discharge corona assisted by V$_2$O$_5$/TiO$_2$ catalyst. Plasma Sci Technol 2004;6:2411–5.

[123] Rajanikanth BS, Srinivasan AD, Das S. Enhanced performance of discharge plasma in raw engine exhaust treatment-operation under different temperatures and loads. Plasma Sci Technol 2005;7:2943–6.

[124] Rajanikanth BS, Sushma BR. Injection of N-radicals into diesel engine exhaust treated by plasma. Plasma Sci Technol 2006;8:202–6.

[125] Rajanikanth BS, Srinivasan AD. Pulsed plasma promoted adsorption/catalysis for NO$_x$ removal from stationary diesel engine exhaust. IEEE Trans Dielectr Electr Insul 2007;14:302–11.

[126] Srinivasan AD, Rajanikanth BS. Pulsed plasma treatment for NO$_x$ reduction from filtered/unfiltered stationary diesel engine exhaust. New Orleans, LA; 2007. p. 1893–900.

[127] Srinivasan AD, Rajanikanth BS. Nonthermal-plasma-promoted catalysis for the removal of NO$_x$ from a stationary diesel-engine exhaust. IEEE Trans Ind Appl 2007;43:1507–14.

[128] Vinogradov J, Rivin B, Sher E. NO$_x$ reduction from compression ignition engines with DC corona discharge: an experimental study. Energy 2007;32: 174–86.

[129] Vinogradov J, Rivin B, Sher E. NO$_x$ reduction from compression ignition engines with pulsed corona discharge. Energy 2008;33:480–91.

[130] Rajanikanth BS, Sinha D, Emmanuel P. Discharge plasma assisted adsorbents for exhaust treatment: a comparative analysis on enhancing NO$_x$ removal. Plasma Sci Technol 2008;10:307–12.

[131] Rajanikanth BS, Mohapatro S, Umanand L. Solar powered high voltage energization for vehicular exhaust cleaning: a step towards possible retrofitting in vehicles. Fuel Process Technol 2009;90:343–52.

[132] Mohapatro S, Rajanikanth BS. Study of pulsed plasma in a crossed flow dielectric barrier discharge reactor for improvement of NO$_x$ removal in raw diesel engine exhaust. Plasma Sci Technol 2011;13(1).

[133] Penetrante BM. Removal of NO$_x$ from diesel generator exhaust by pulsed electron beams. In: Proceedings of the 11th IEEE International pulsed power conference, 1997 digest of technical papers, vol. 1; 1997. p. 91–6.

[134] Behbahani HF, Fontijn A, Muller-Dethlefs K, Weinberg FJ. The destruction of nitric oxide by nitrogen atoms from plasma jets. Combust Sci Technol 1982;27:123–32.

[135] Penetrante BM. NO$_x$ reduction by electron beam-produced nitrogen atom injection. United States; 2000.

[136] Masuda S, Hirano M, Akutsu K. Enhancement of electron beam denitrization process by means of electric field. Radiat Phys Chem 1977;1981(17):223–8.

[137] Ravi V, Mok YS, Rajanikanth BS, Kang HC. Temperature effect on hydrocarbon-enhanced nitric oxide conversion using a dielectric barrier discharge reactor. Fuel Process Technol 2003;81:187–99.

[138] Magureanu M, Pârvulescu VI. Plasma-assisted NO$_x$ abatement processes: a new promising technology for lean conditions. In: Granger P, Pârvulescu VI, editors. Studies in surface science and catalysis. Netherlands: Elsevier; 2007. p. 361–96 ([chapter 12]).

[139] Penetrante BM, Hsiao MC, Bardsley JN, Merritt BT, Vogtlin GE, Wallman PH, et al. Electron beam and pulsed corona processing of volatile organic compounds and nitrogen oxides. In: Proceedings of the 10th IEEE international pulsed power conference, digest of technical papers, vol. 1; 1995. p. 144–9.

[140] Penetrante BM, Hsiao MC, Bardsley JN, Merritt BT, Vogtlin GE, Wallman PH, et al. Electron beam and pulsed corona processing of volatile organic compounds and nitrogen oxides. In: Proceedings of the 10th IEEE international pulsed power conference. Albuquerque; 1995.p. 144–9.

[141] Hoard J, Laing P, Balmer M, Tonkyn R. Comparison of plasma-catalyst and lean NO$_x$ catalyst for diesel NO$_x$ reduction. SAE technical paper 2000-01-2895; 2000.

[142] Konuma M. Film deposition by plasma techniques. Springer-Verlag; 1992 ISBN 978-3-642-84511-6, Germany.

[143] Takaki K, Hatanaka Y, Arima K, Mukaigawa S, Fujiwara T. Influence of electrode configuration on ozone synthesis and microdischarge property in dielectric barrier discharge reactor. Vacuum 2008;83:128–32.

[144] Arai M, Saito M, Mitsuyama Y. Continuous regeneration of an electrically heated diesel particulate trap. Int J Engine Res 2007;8:477–86.

[145] Kobayashi Y, Furuhata T, Amagai K, Arai M. Soot precursor measurements in benzene and hexane diffusion flames. Combust Flame 2008;154:346–55.

[146] Mok YS, Lee H-J. Removal of sulfur dioxide and nitrogen oxides by using ozone injection and absorption–reduction technique. Fuel Process Technol 2006;87:591–7.

[147] Thagard SM, Kinoshita Y, Ikeda H, Takashima K, Katsura S, Mizuno A. NO$_3$-reduction for NO$_x$ removal using wet-type plasma reactor. Ind Appl IEEE Trans 2010;46:2165–71.

[148] Yamamoto T, Yang CL, Beltran MR, Kravets Z. Plasma-assisted chemical process for NO$_x$ control. IEEE Trans Ind Appl 2000;36:923–7.